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VERIFICATION OF CRYOGENIC BLOWOUT CONTROL  
TECHNOLOGY FOR OFFSHORE OIL WELLS,  
FINAL REPORT

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## FOREWORD

This final report, BDM/A-81-706-TR, was prepared by The BDM Corporation, 1801 Randolph Rd. S.E., Albuquerque, New Mexico 87106, and is submitted in accordance with Article II of contract number 14-08-0007-20218 to the U.S. Geological Survey, Reston, Virginia.

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## DSD FINAL REPORT

### A. INTRODUCTION

This report describes the BDM laboratory test program which successfully demonstrated the functional principal of a cryogenic blowout control device for offshore oil wells. The device, which would first be placed downhole as part of the casing string while drilling and later be part of the production tubing, will be referred to as a Downhole Shut-In Device (DSD).

A scale model of the DSD was tested to demonstrate the "proof of principle" of the technology required to shut in a blown-out oil well. The test program had two objectives:

- (1) Parametrically verify that a naturally depleting oil well can be shut in by formation of a frozen plug of well fluid.
- (2) Parametrically verify that the frozen plug can withstand the static pressure resulting in the shut-in well.

This report is divided into six sections. Section B which follows, presents background material on blown-out oil wells and a description of the full scale DSD, section C summarizes the test program giving major results and conclusions, section D presents the detailed technical approach, section E gives test results, and F gives conclusions and recommendations.

### B. BACKGROUND

Regaining control of a high-pressure, offshore oil well which has blown out or suffered damage is a time consuming and hazardous operation. The uncontrolled flow of oil produces severe pollution and waste problems, and attempts to regain control often result in severe injury or death. At best, oil well blowouts result in astronomical financial losses and major environmental problems.

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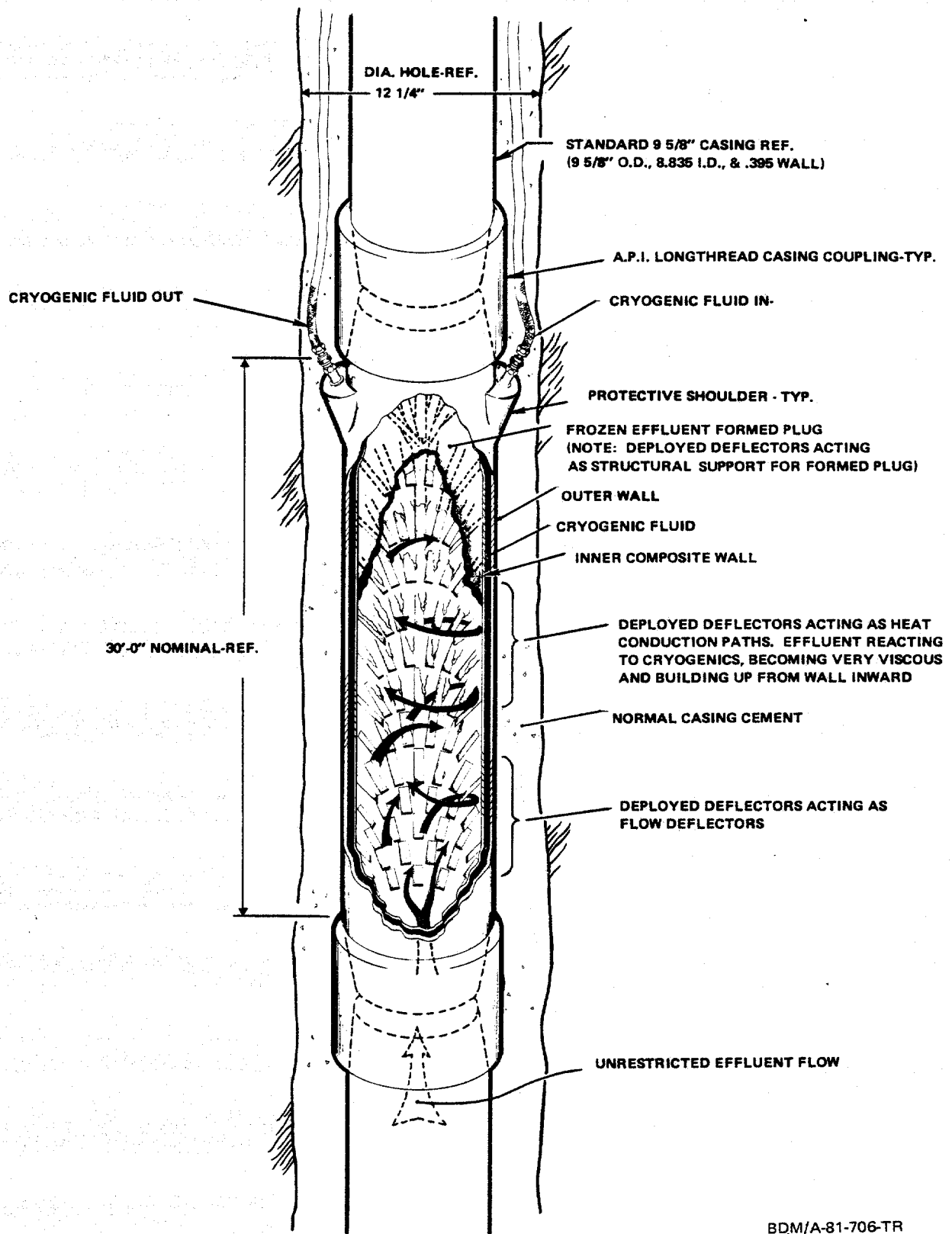
The present state-of-the-art of oil well disaster control relies principally on prevention. Blowout preventers are used during the drilling process and downhole storm chokes are found on producing off-shore wells. The blowout preventer is a fairly reliable device and, when properly operated, serves its function well. Storm chokes, on the other hand, are soon degraded by their operating environment and frequently fail to perform their intended function.

Regardless of the reliability of the present state-of-the-art techniques, there are failures and every year the same cycle of disaster repeats itself. One approach to mitigating the effects of an out-of-control oil well is to develop a safe and effective means of regaining control after the blowout occurs. As a step toward this goal BDM proposed and conducted a "proof of principle" demonstration of technology that would rapidly shut in a blown-out well, minimize financial loss and environmental damage, and virtually eliminate the safety hazards normally associated with blowout control.

The technology proposed by BDM places a DSD in the oil well at a depth dictated by the casing plan (as an example, the placement depth in an offshore well being drilled might reach 4000 feet). The DSD would be temperature-actuated to stop the flow of the well fluids by the formation of a frozen plug (the term frozen is not necessarily used in its strict technical sense). The effluent in a freely depleting, or blown-out oil well, is made up of varying amounts of oil, water, and gas which exist in the various phases. The technology proposed here involves directing these fluids onto extremely cold surfaces which will result in the formation of a frozen plug of the well effluent. The device designed to accomplish this is the DSD shown pictorially in figure 1.

The DSD would be installed as a part of the casing string while drilling the well, and later as a part of the production tubing during oil well completion. The device is applicable to both the drilling process, offering no interference with tools, methods, or procedures, and to the production process, where damage caused by ship collision or storms could result in loss of well control.

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Figure 1. Enlarged Section of the DSD Concept

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The DSD is nearly identical to a joint-of-oil field casing in size and shape. It will be constructed from high-strength, cryogenically compatible material such as 304 stainless steel. It is compatible with present oil field handling equipment, casing, couplings, and all oil field materials and chemicals. The inside diameter of the DSD is identical to the casing string in which it is installed; the outside diameter, although slightly larger than its companion casing, is sized to fit through the same wellbore or other casing strings that its companion casing is designed to fit through.

The volume through which the cryogen from the surface will flow is shown in figure 1, just inside the outer wall. This volume extends throughout the length of the DSD. When the DSD is activated, the cryogen will flow through a line (or lines) from a manifold located in a secure place remote from the well area. The incoming cryogen will absorb the heat supplied to the DSD by the well fluids.

Directly inside the cryogen volume is the inner composite wall. The function of this wall is to provide an inside diameter equal to that of the casing string into which the DSD has been integrated; to provide housing for, and a structural base to, the flow directors; and to act as the heat transfer medium between the cryogen and the well fluids. A detailed drawing of the construction concept of the flow directors is illustrated by figure 2.

These flow directors are not configured in groups, but are located in helical patterns along the length of the DSD, such that flow transparency and optical density are retained. Flow will then be constrained generally along the helix, further lengthening the contact time during which heat transfer will occur.

Since each flow director lies flush with the inside surface of the DSD, it lies within the boundary layer of the flowing fluid. The laws of fluid mechanics provide that, regardless of the velocity of flow in the center of the wellbore, the velocity is essentially zero at the wall, thereby helping to isolate the stowed flow directors from the dynamics of the uncontrolled flow of well fluids.

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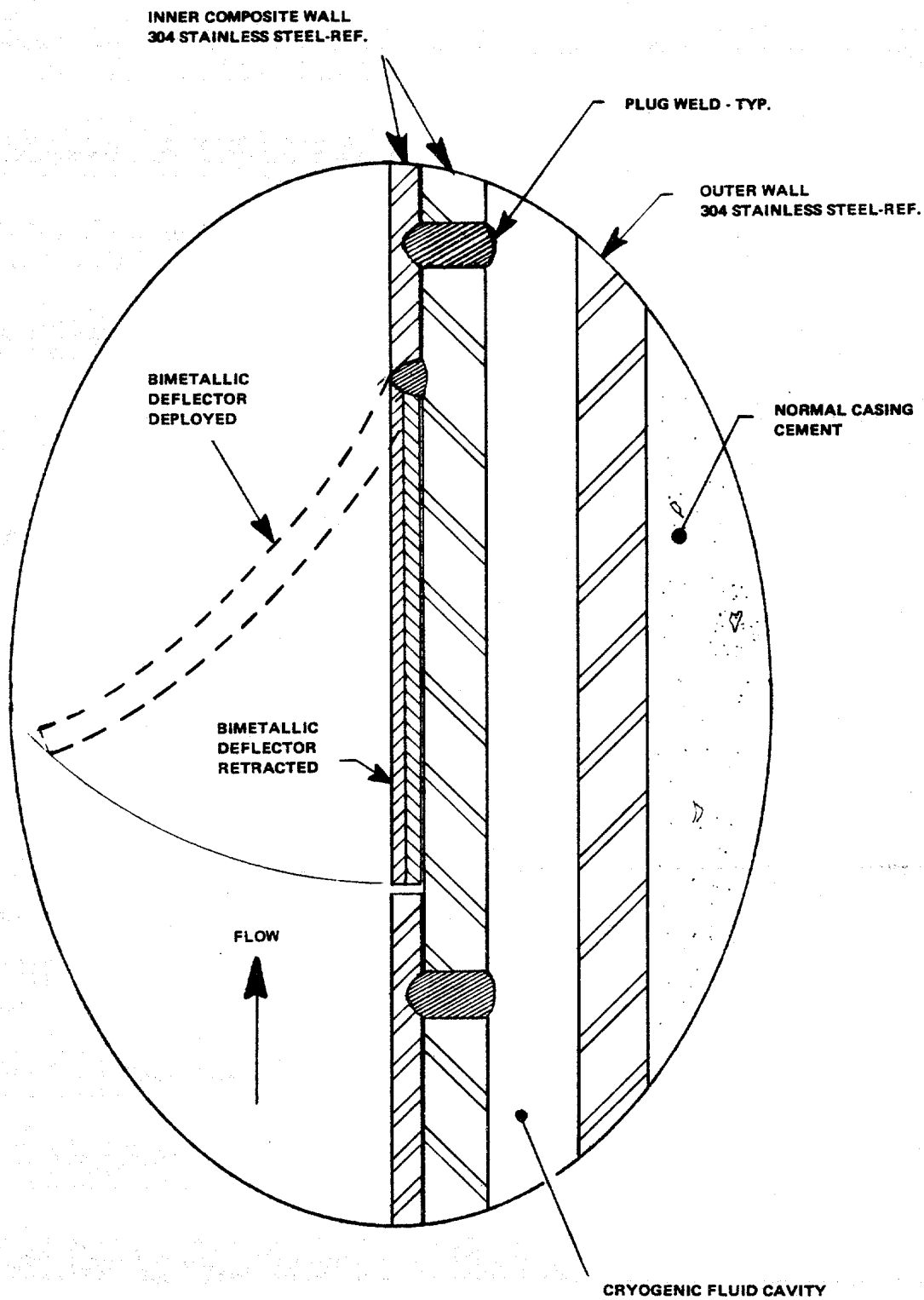


Figure 2. DSD Wall/Deflector Detail

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Deployment of the flow directors is accomplished in two steps. First, the temperature of the flow director is reduced at a rate that will cause the bi-metallic structure to produce a distortion such that the free end projects out of the boundary layer and into the high-velocity flow of well fluid. Second, the director is deployed to a defined limit by the dynamic pressure applied to the free end by the well fluid. The structure of the flow director is such that upon return of control to the oil well and return of temperatures to normal, the flow directors will yield to the designed preload and return to their stowed position, flush with the inner composite wall of the DSD.

The principle of the cryogenic DSD is based on the transfer of heat from the flowing petroleum to the cryogen. Crude oil has a strongly temperature-dependent viscosity and will build up as a waxy layer on the condensing surfaces within the DSD near the exit end. The buildup of the oil layer will be facilitated by artificially roughening the condensing surface with shallow grooves. This will increase the surface area for heat transfer and also help secure the frozen plug to the wall. Initial plug formation is expected to be rapid, but total closure will depend on the heat transfer coefficient of the oil/gas mixture as it varies with time and position along the axis of the heat exchange region.

When drilling or production operations are conducted with the well under control, the fluid between the walls of the DSD will be a non-compressible liquid. This liquid will allow transmission of well pressures from the relatively weak composite wall to the structural outer wall. When shutting the well in, the liquid will first be purged with dry gaseous nitrogen, followed by nitrogen of successively lower temperatures until only liquid nitrogen is present. After the flow directors are deployed, the frozen plug formed, and repairs made, the liquid nitrogen will be purged by dry gaseous nitrogen, the non-compressible liquid will then be replaced, and the pressure will be equalized. The flow deflectors will return to their normal position, flush with the inner composite wall.

BDM investigated the DSD technology described above by conducting laboratory tests on a scale model. The tests provided positive answers

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to the two questions which were to be answered by the test program (1) can the DSD form a frozen plug of the well fluids? and (2) can the formed plug withstand the full extent of the bottom hole pressure and retain its integrity? The results of BDM's test program are summarized below.

### C. SUMMARY

BDM completed a test program on a one-quarter scale model of the downhole shut-in device to demonstrate the "proof of principle" of the technology for using a cryogenic device to control blowing-out oil wells. The primary objectives of the test program were to demonstrate that the proposed technology could be used first to stop the flow of oil through a simulated section of a well by the formation of a frozen plug and then to maintain the frozen plug under pressure conditions.

The technical approach used in conducting the test program consisted of gathering information which defined or characterized actual wells; developing simulation techniques for the development of the scale model; designing the test section and related test support equipment; developing pressure, temperature, and flow instrumentation and data acquisition; and conducting a series of tests which could demonstrate the desired proof of technology.

The resulting device consisted of a one-quarter scale model of the DSD with supporting equipment to produce the desired oil flow through the test section, provide a supply of cryogen to the test section, monitor temperature, pressure, and flow, and allow for the necessary transfer and heating of oil prior to testing. Figures 3 and 4 show the completed test installation. The larger diameter vertical members are the two scale model DSD test sections used in the experiment.

Using the scale model device, eleven tests were conducted on an intermittent basis between November 1981 and February 1982. Four tests were conducted using one test section, five with two test sections, eight with crude oil only (39° API crude was used), and three with oil/gas mixtures. Testing in the quarter scale model included oil flow rates

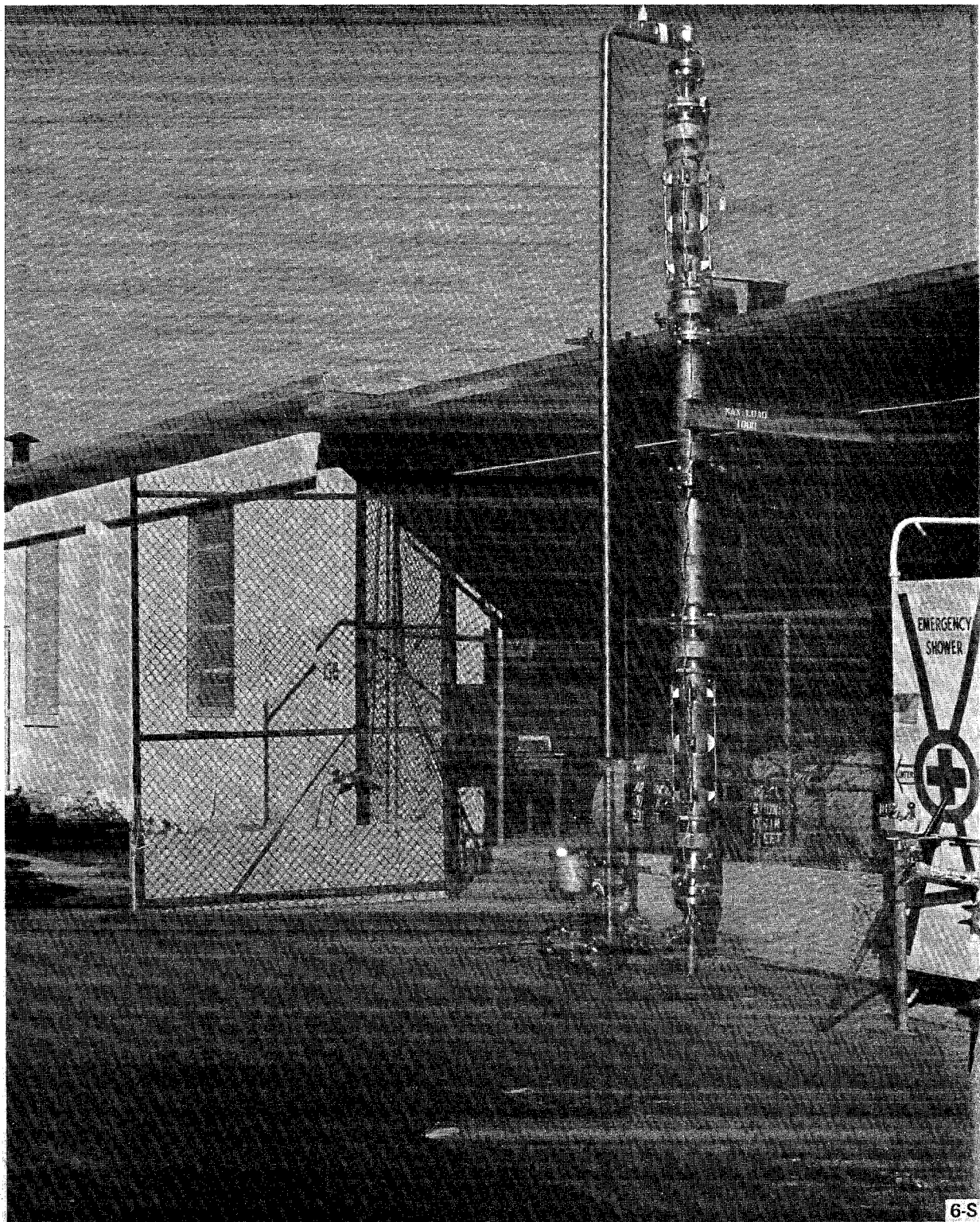


Figure 3. DSD Model Installation

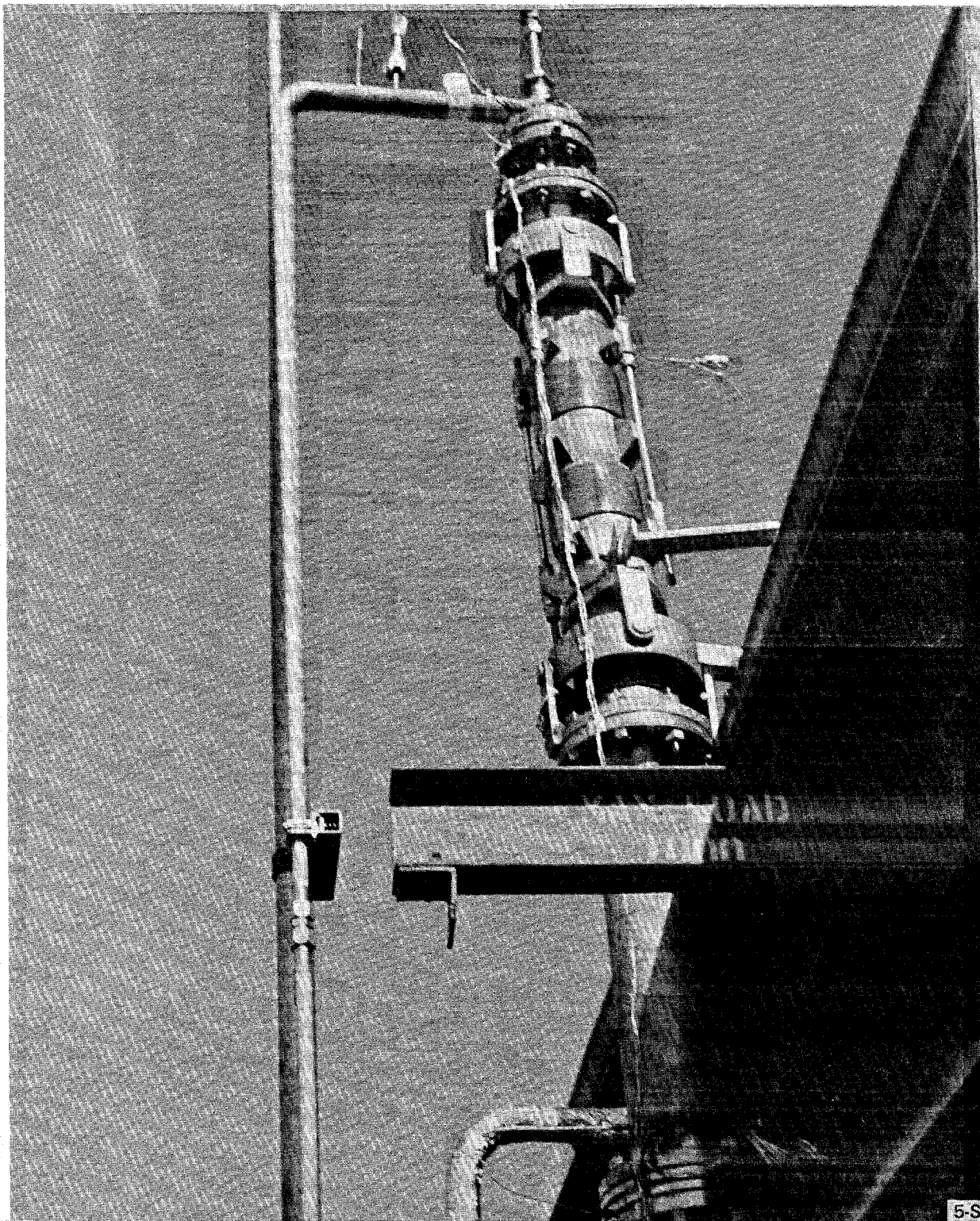


Figure 4. DSD Model Test Section

ranging from 3.8 gpm to 7.4 gpm which extrapolates to flows of 520 to 1015 gpm in a full scale device. In all cases, the flowing fluid was effectively stopped by the formation of a frozen plug and the integrity of the frozen plug was demonstrated by pressure testing up to 400 psig.

The results of this project have demonstrated that, in a one-quarter scale laboratory experiment, a cryogenic device can be used to effectively stop a flow of crude oil at flow rates of approximately 4 to 7 gpm in 20 to 30 minutes. Based on some fairly simplified modeling techniques it would be expected that, for similar fluids, the heat transfer coefficient in a full scale device would be one-fourth that of the model.

Three deviations from the proposed program plan should be noted. (1) Oil supply temperatures were approximately 16°C while the established temperature for the representative well was 75°C and further testing with elevated oil temperatures is recommended. The desired oil supply temperature was not achieved because of electrical power supply problems at the test site, low ambient temperatures, and heat losses in uninsulated components. (2) Water mixtures were not used and it was concluded prior to testing that the addition of water would expedite freezing. Also, more effective use of test resources would be made by testing oil or oil/gas mixtures. Further testing of oil/gas mixtures is recommended to quantify the device performance with oil/gas mixtures. Modification of the test system is necessary to measure gas flow rates. (3) Strain measurements were not taken at the deflection blades because the strain gauges were not available during test section assembly. A stress analysis, conducted in lieu of strain measurements, indicated that the deflector design used would restrain a frozen plug during oil pressures up to 39000 psi in a full scale device, which is well above the maximum downhole pressure of 20000 psi established for the representative well.

It is recommended that an analytical program be implemented to quantify the physical phenomenon; further testing be conducted using the existing one-quarter scale device to resolve oil supply temperature effects, measure gaseous nitrogen flow rates to quantify oil/gas mixtures, and measure liquid nitrogen flow rates; a prototype be designed for operational testing and refinement at LSU, and an actual oil well device be designed and fabricated for testing in an actual well.

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### D. TECHNICAL APPROACH

The technical approach used in conducting the "proof of principle" laboratory tests for the DSD was to first gather information which defines or characterizes actual wells, second, develop simulation techniques for the development of a scale model demonstration device which would allow extrapolation of test results to full scale wells, third, design the test section and related test support equipment for producing the desired test program, forth, instrument the test system in a manner which monitors test conditions of interest, fifth, develop a data acquisition/display system to enable recording and manipulation of test parameters, sixth, plan and conduct a series of tests which demonstrate the desired "proof of principle," and finally, document the test program.

#### 1. Oil Well Characterization and Parameter Definition

The effluent in a freely depleting or blown-out oil well is made up of varying amount of oil, water, and gas which exist in various phases. The characterization of a blown-out oil well consists of:

- a. Defining the effluent (What are the constituents, their proportions, and physical properties of the mixture?)
- b. Defining the temperature and pressure conditions under which the effluent exists at a potential DSD location in the well.
- c. Defining the mixture flow rate at the point of interest.
- d. Defining the geometry of the passageway through which the mixture flows.

Attempts were made to compile oil well characterization data from the literature and from telephone conversations with individuals from the USGS, The BDM Corporation, oil companies, universities, and an oil well fire and blow-out control company. The results of this investigation follow.

#### a. Effluent Mixture and Flow Rate

There is a wide variance in the amount of fluid flowing, and ratio of constituents, in blowing-out wells. One thousand barrels of

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multiphase fluid per day is an average significant blow-out in the United States oil fields. Larger blow-out rates are of course possible. The exploratory well in the Gulf of Mexico which blew out in 1979 was estimated to be flowing at about 20,000 barrels of liquid oil per day. The amount of well flow is dependent upon casing size, reservoir size, formation pressure, and any obstructing equipment in the well or on the well head.

In addition to the wide variance in rate of effluent flow, the proportions of constituents also vary greatly. Blown-out wells have been observed to vary from almost 100 percent crude oil to almost 100 percent methane gas, with possible intermediate mixtures of various amounts of oil, gas, water, and particulate matter such as sand.

From this investigation of effluent flow rates and mixture proportions it was concluded that a flow of 1,000 barrels per day of a mixture varying from pure crude oil to crude oil and gas would be reasonable for conducting the test. It was also concluded that eliminating water from the mixture provided a worst-case test since the water would expedite the freezing process. The addition of particulates, such as sand, to the mixture would add serious contamination problems to the flow meter and valves without significantly contributing to the test objectives.

### b. Temperature and Pressure

In an oil well, the highest temperature encountered at which liquid hydrocarbon is found is 150°C (302°F). Although it will lose much of its heat as it moves to the surface, the emerging fluid could be as hot as 60°C (140°F). These figures bracket the temperatures at the extremes - bottom hole and surface. What is required is a representative temperature at a potential DSD location in the well.

One formula for formation temperatures (in degrees F) versus depth is given by  $T_D = T_a + aD$  where  $T_a$  is surface temperature,  $T_D$  is temperature at a depth D, D is depth in hundreds of feet, and (a) is a temperature gradient. According to Gatlin,\* page 29, a representative gradient is .89°C/100 ft (1.6° F/100 ft).

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\*Gatlin, Carl, "Petroleum Engineering, Drilling and Well Completions," Prentice-Hall, Inc., 1960

Using an average temperature at the surface of 27°C (80°F) and a reservoir depth of 8000 ft one gets a bottom hole temperature of 98°C (208°F). Then, based on Gatlin, page 108, it is estimated that for a flowing well with a depth of 8000 ft, the temperature of the fluid at a DSD located at 4000 ft would be approximately 75°C (168°F).

The decision was made to use a maximum oil supply temperature of 75°C and maximum design pressure for the test system of 500 psig. As will be noted later, the desired temperature of the oil into the test section of 75°C could not be achieved with the test layout because of electrical power supply problems at the test site, low ambient temperatures, and high heat losses although attempts were made to raise the oil temperature using immersion heaters and oil supply tank insulation. However, it will be shown later that test results indicate that freezing time may be somewhat independent of oil inlet temperature.

As discussed previously, bottom hole pressure in an actual well can be as high as 20,000 psi. However, it is unnecessary and costly to attempt to simulate pressures of this magnitude. The test system needs to be capable of those pressures required to produce the desired flow and pressure testing on the frozen plug. Also, the effects of actual well pressures on the fluid state must be addressed.

c. Geometry

Overall dimensions of the DSD could be the same as for any of the standard well casings in use. For purposes of this program, a standard 9 5/8 inch (9 5/8 O.D., 8.835 I.D.) casing, 30 feet long was assumed.

2. Simulation Techniques

As stated previously, the primary objective of this program is to demonstrate the "proof of principle" of the DSD using a scale model or laboratory test as opposed to an actual oil well. (The use of a scale model for the test is necessary because of budget constraints and is in tune with the primary objective of demonstrating that the principle works.) Another objective was to correlate the laboratory test results with a full scale device.

These objectives led to the development of simulation techniques to produce a model from which results could be extrapolated.

To investigate simulation requirements, a dimensional analysis was performed on the freezing portion of the downhole choke test device. The thickness of the frozen oil layer was assumed to depend on the following parameters.

$h$ :	connective heat transfer coefficient
$T_f - T_w$ :	$\Delta T_w$ between the freezing temperature and wall temperature
$T_o - T_f$ :	$\Delta T_o$ between inlet temperature and freezing temperature
$P_o - P_l$ :	$\Delta P$ between inlet and outlet pressure
$L$ :	length of freezing section
$D$ :	Diameter of freezing section
$V$ :	Fluid velocity
$k_s$ and $k_l$ :	Thermal conductivity of frozen solid and liquid
$\rho_s$ and $\rho_l$ :	Density of solid and liquid
$Cp_s$ and $Cp_l$ :	Specific heat of solid and liquid
$\tau$ :	time
$\lambda$ :	Heat of fusion

Dimensional analysis gives a function form

$$\frac{\delta}{D} = F \left[ \begin{matrix} (1) & (2) & (3) & (4) & (5) & (6) & (7) & (8) & (9) & (10) & (11) & (12) \\ \frac{k_s}{k_l}, & \frac{C_{p_l} \mu}{k_l}, & \frac{\rho_s}{\rho_l}, & \frac{C_{p_s}}{C_{p_l}}, & \frac{k_l \Delta T_o}{k_s \Delta T_w}, & \frac{\lambda}{C_{p_l} \Delta T_w}, & \frac{P_l V D}{\mu}, & \frac{h D}{k_s}, & \frac{\rho_l V^2}{\Delta P}, & \frac{L}{D}, & \frac{L}{V \tau}, & \frac{k_s \tau}{\rho_s C_{p_s} D^2} \end{matrix} \right]$$

where  $\delta$  is the frozen layer thickness.

These dimensionless ratios are typical of the dependences found in various investigations of freezing of flowing liquids in a pipe. What is missing is the effect of the bi-metallic "deflectors" extending into

the flow. These deflectors should enhance the freezing process since they increase turbulence and provide more surface area for heat removal. However, the inclusion of these deflectors in the simulation analysis is beyond the scope of this contract and should be addressed in another phase.

By letting  $V=G/A$ , where  $G$  is the volume flow rate and  $A$  is the area of the pipe cross section, the functional form becomes

$$\frac{S}{D} = F \left[ \begin{matrix} (1) & (2) & (3) & (4) & (5) & (6) & (7) & (8) & (9) & (10) & (11) & (12) \\ \frac{k_s}{k_l}, & \frac{C_p \mu}{k_l}, & \frac{\rho_s}{\rho_l}, & \frac{C_{p_s}}{C_{p_l}}, & \frac{k_l \Delta T_o}{k_s \Delta T_w}, & \frac{\lambda}{C_p \Delta T_w}, & \frac{\rho G}{\mu D}, & \frac{hD}{k_s}, & \frac{\rho_l G^2}{\Delta P D^4}, & \frac{L}{D}, & \frac{LD^2}{G \tau}, & \frac{k_s \tau}{\rho_s C_{p_s} D^2} \end{matrix} \right]$$

For similarity between the model and full scale device each of these dimensionless ratios for the model must be the same as for the full scale device. The ratios were examined for a one-quarter scale model.

A one-quarter scale model was selected since that provided a reasonable size (and cost) to work with. Then for geometry:  $D_m = 1/4D$  and  $L_m = 1/4L$  when the subscript  $m$  refers to the model. Since the diameter of the representative full scale DSD is 8.835 inches and the length of 30 ft is typical, the model dimensions are

$$\begin{aligned} D_m &= 2.21 \text{ inches} \\ L_m &= 7.5 \text{ ft} \end{aligned}$$

With the model geometry established, the parameter changes necessary for similarity between the model and full scale device were addressed. The assumption was made that the fluid used in the model would be the same as that in the full scale device; therefore, all the dimensionless ratios containing only material properties would be the same for the model and full scale devices. Ratios (1), (2), (3), and (4).

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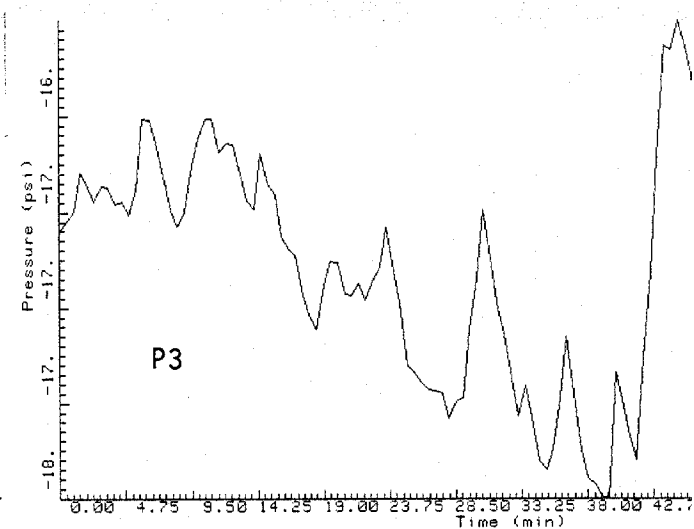
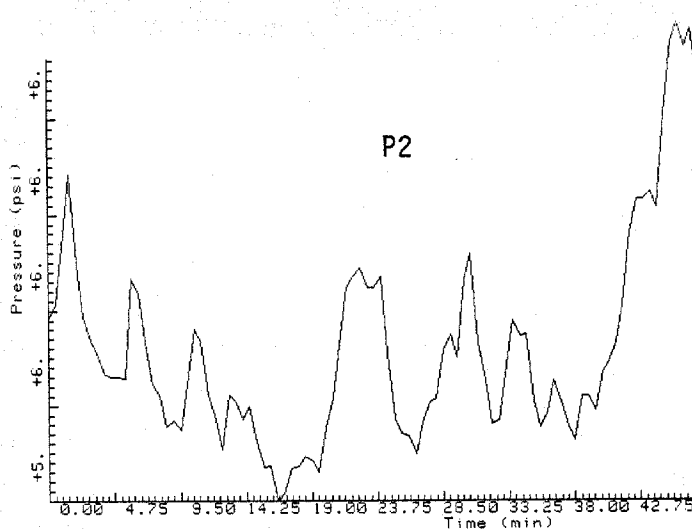
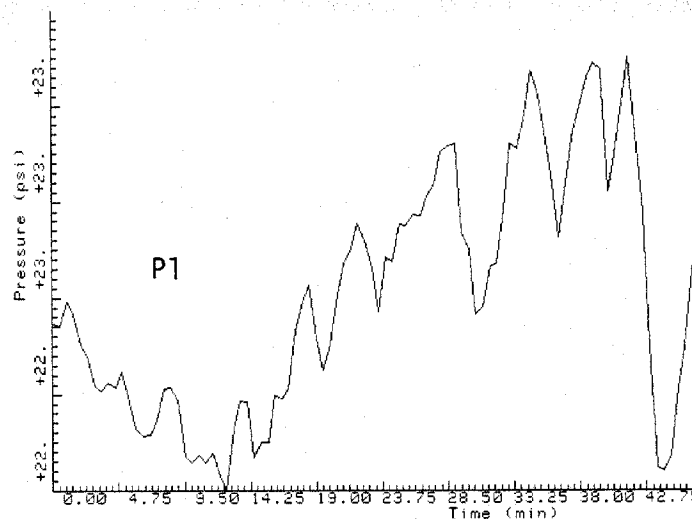
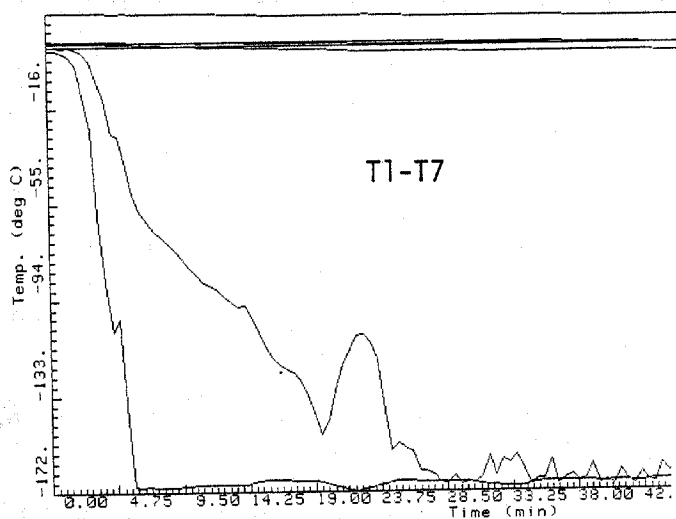
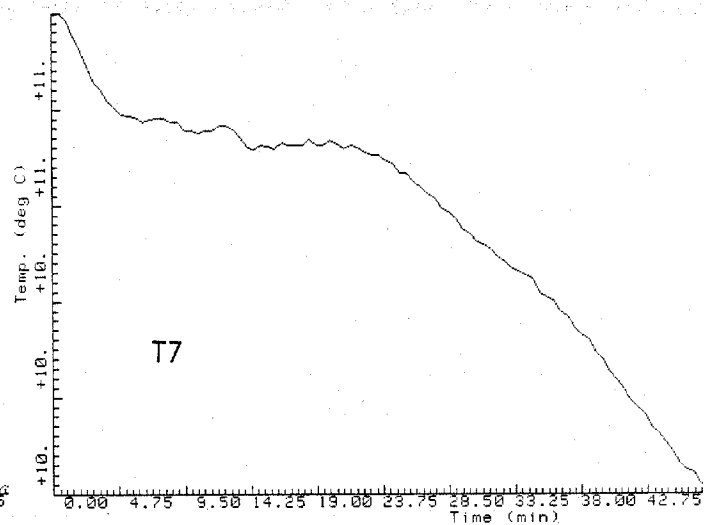
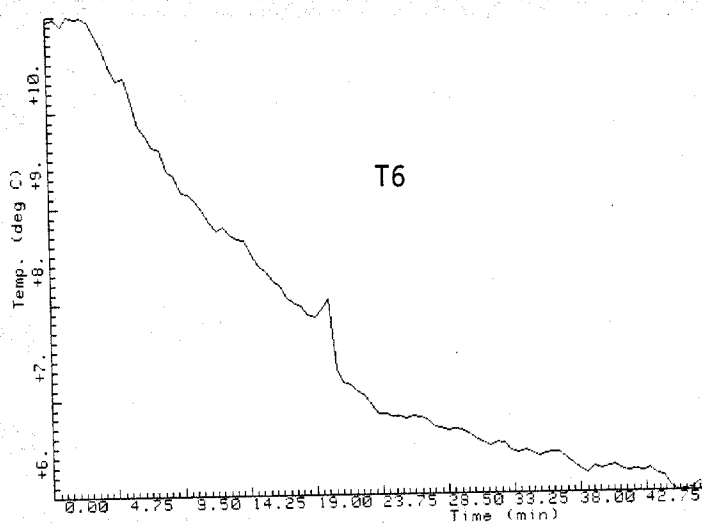
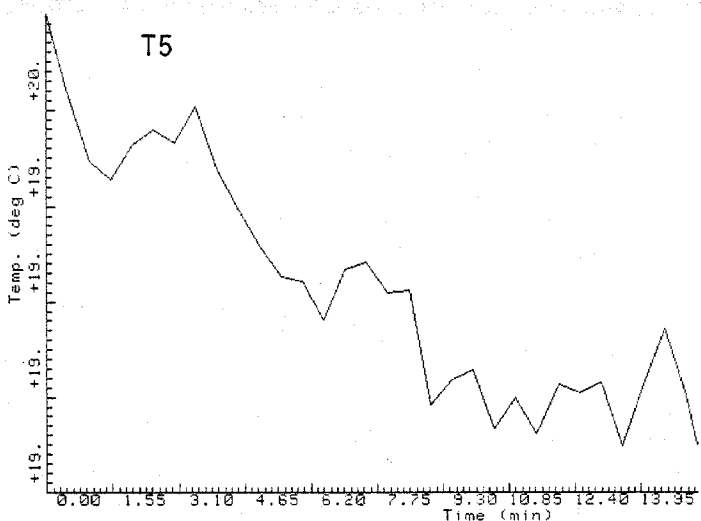
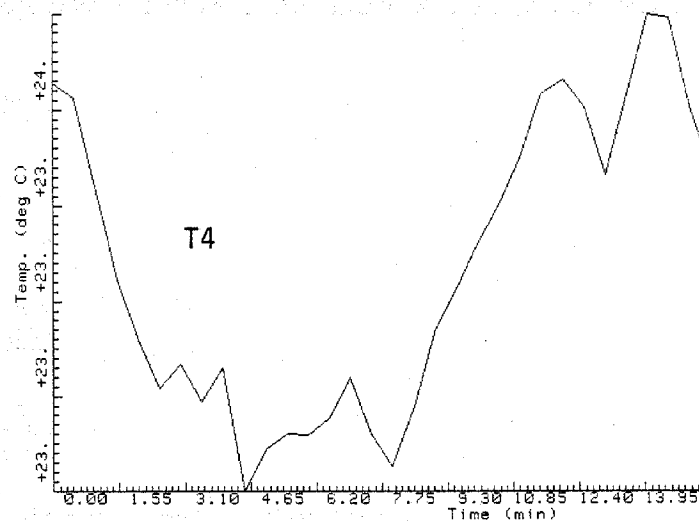
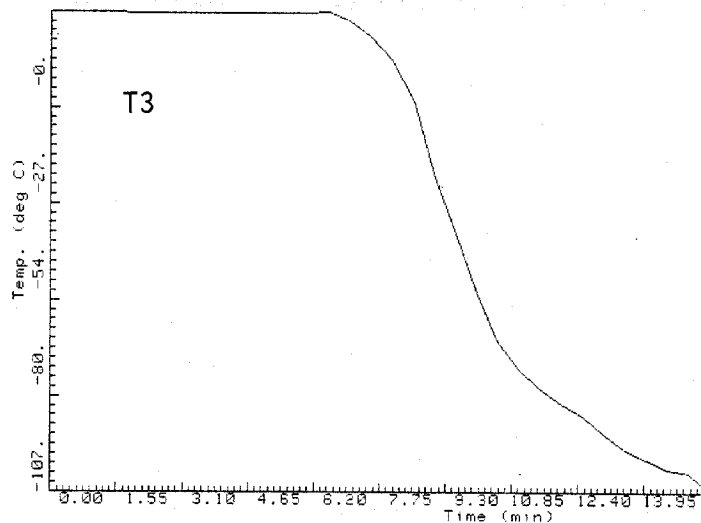
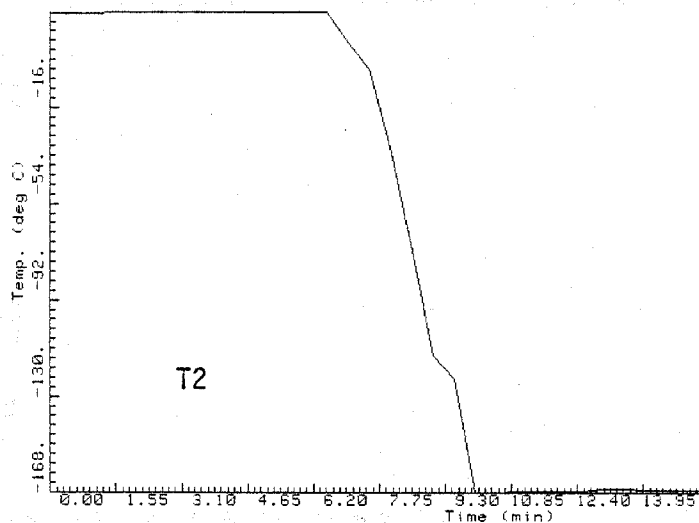
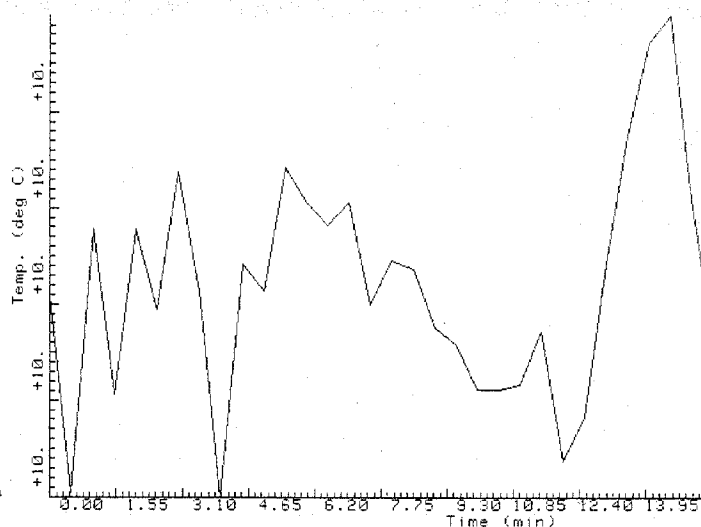
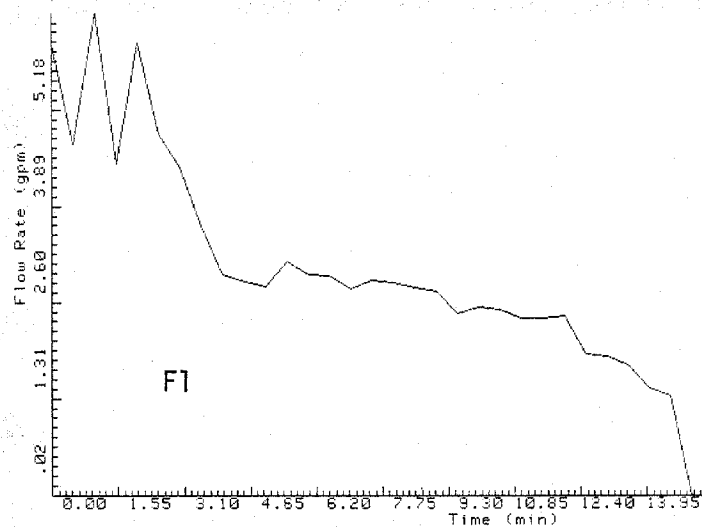


Figure A-1. TEST 1 Results (Concluded)

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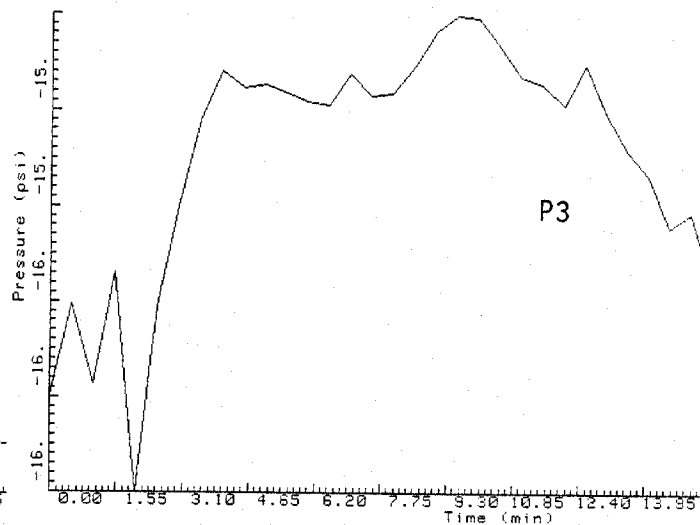
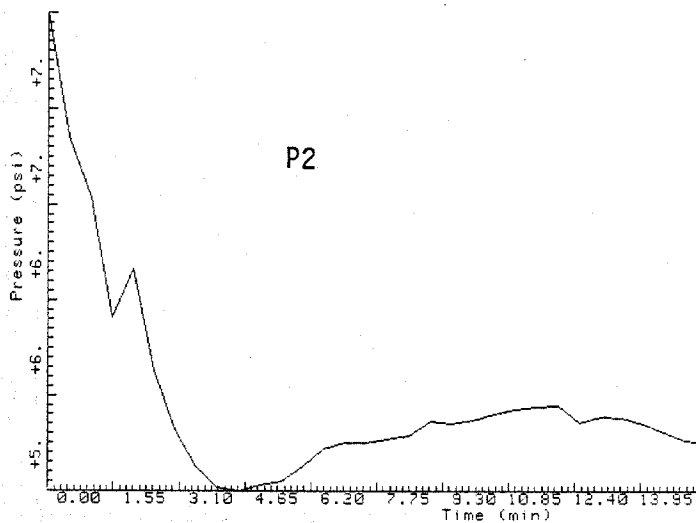
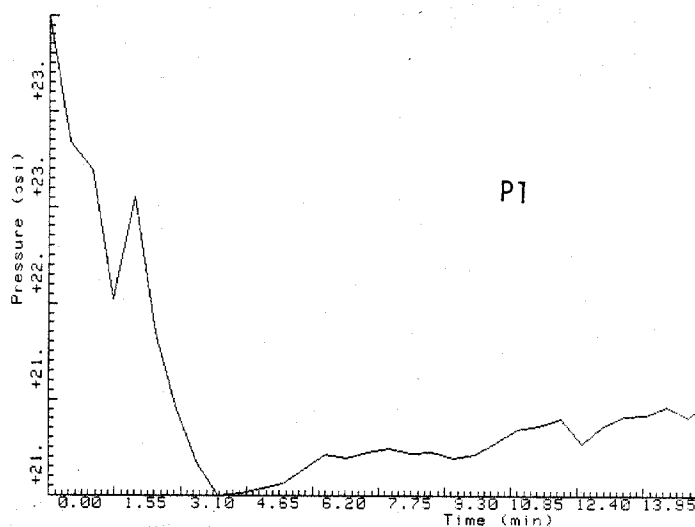
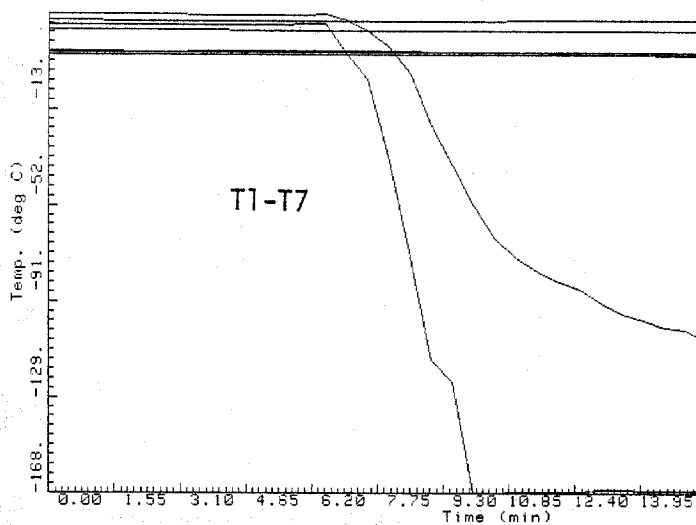
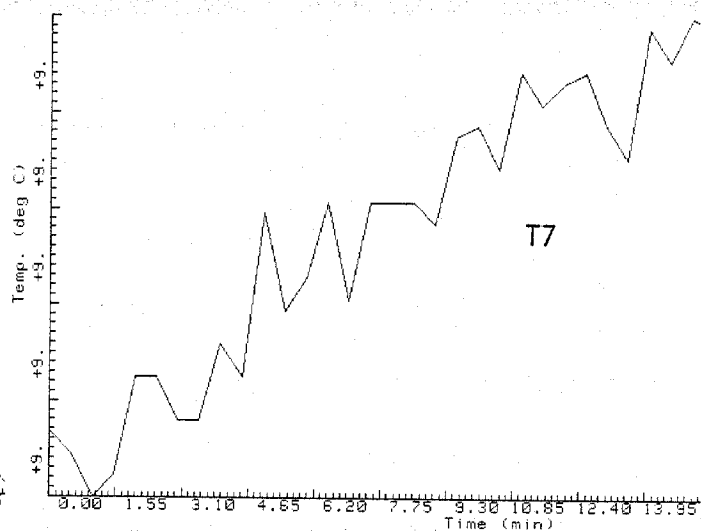
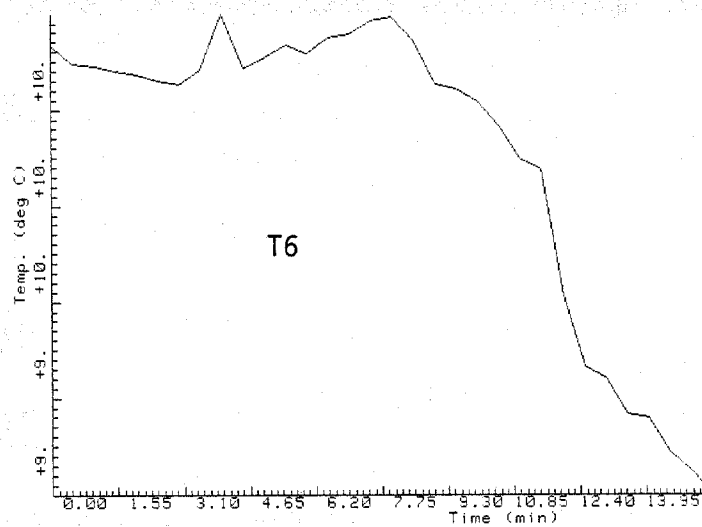
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Figure A-2. TEST 2 Results

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Figure A-2. TEST 2 Results (Concluded)

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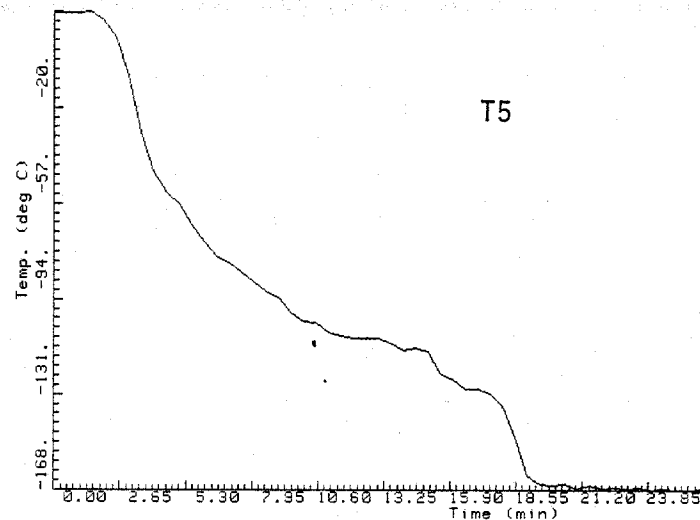
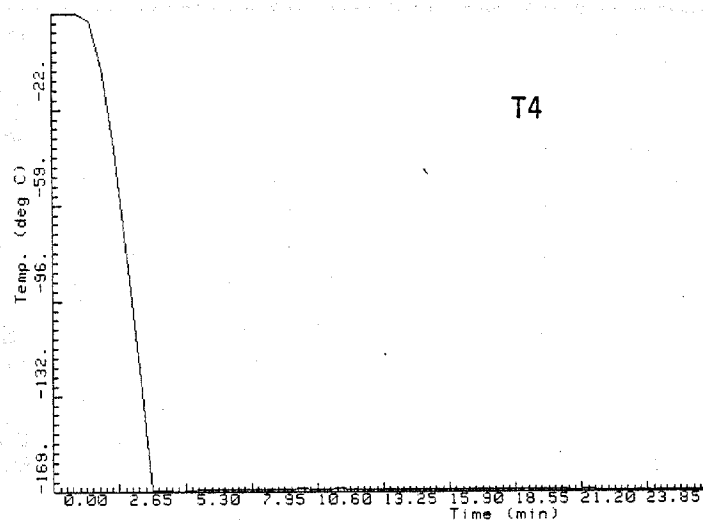
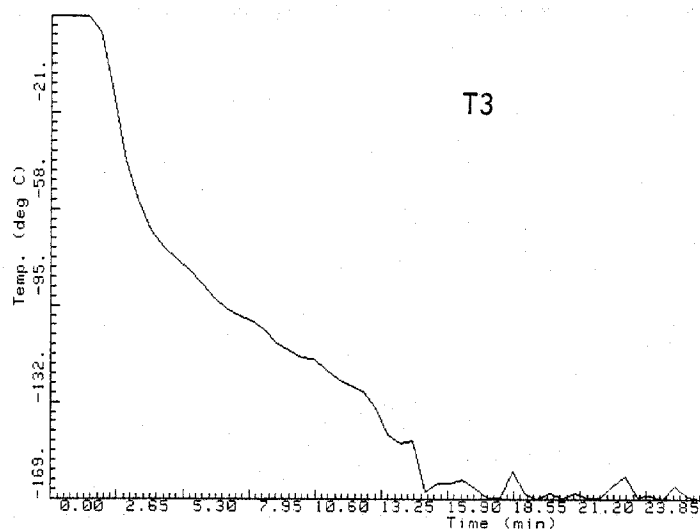
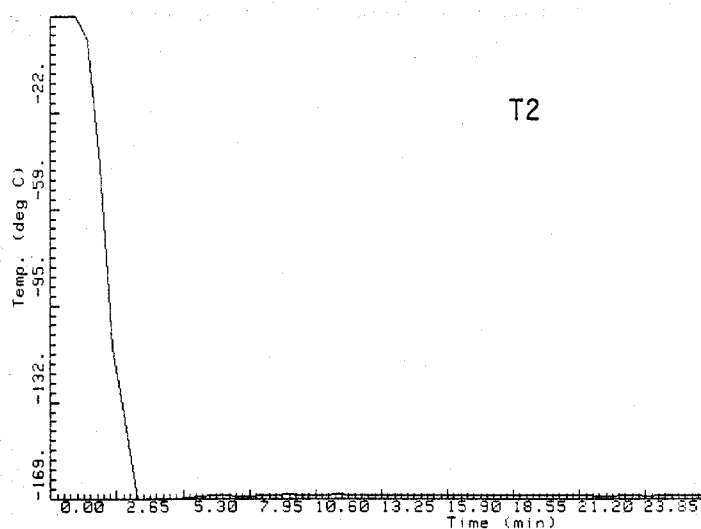
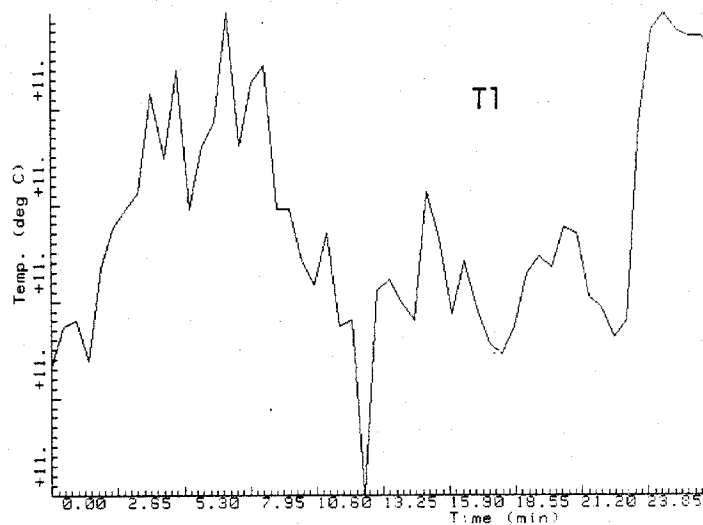
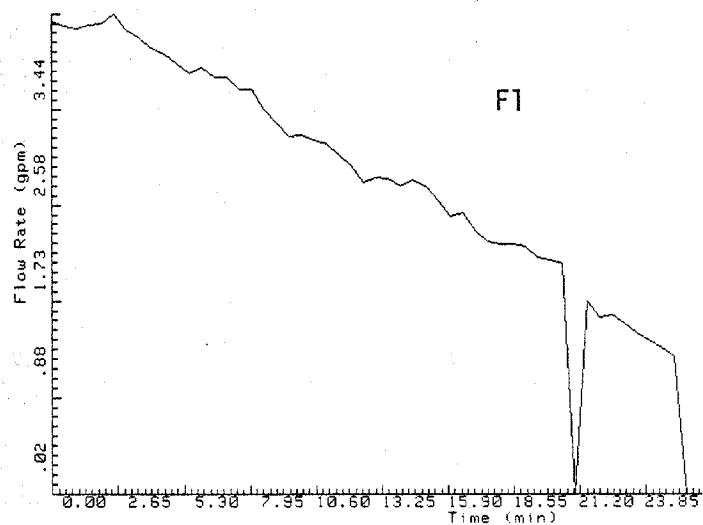
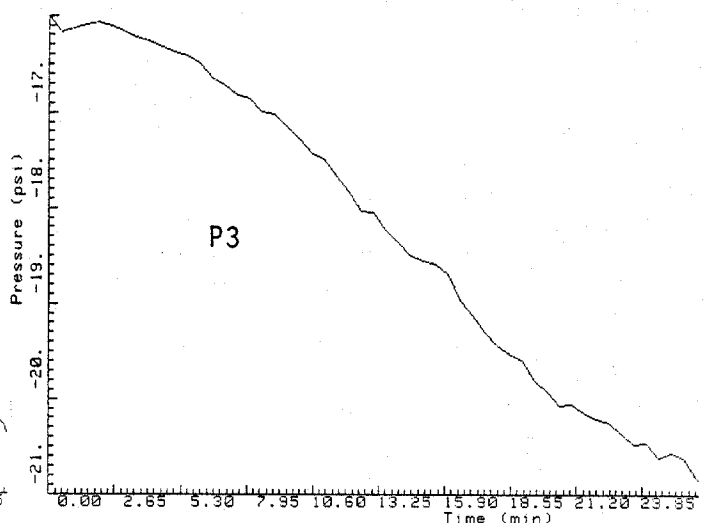
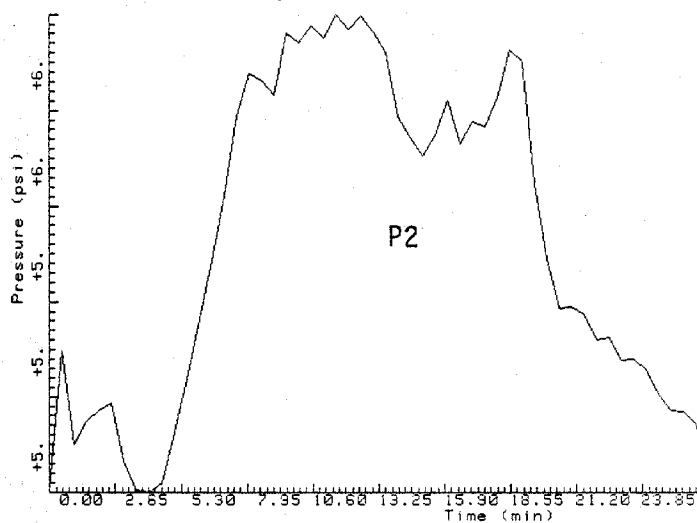
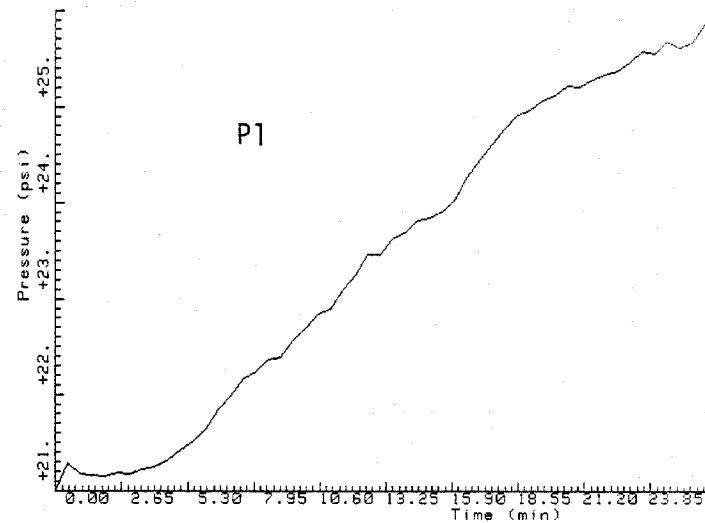
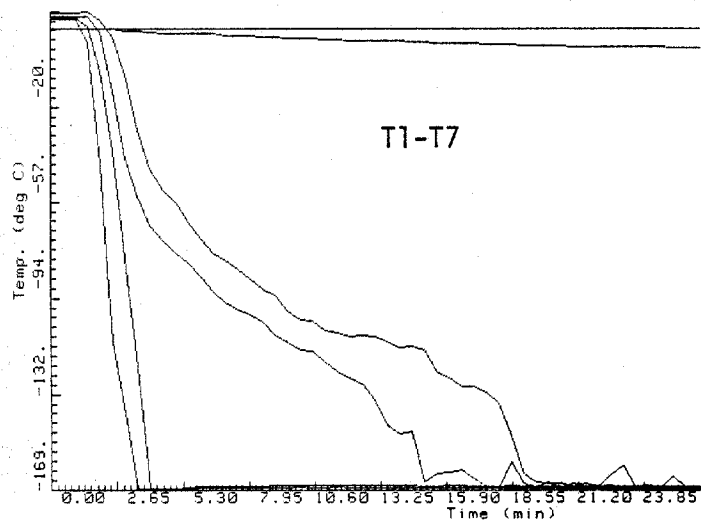
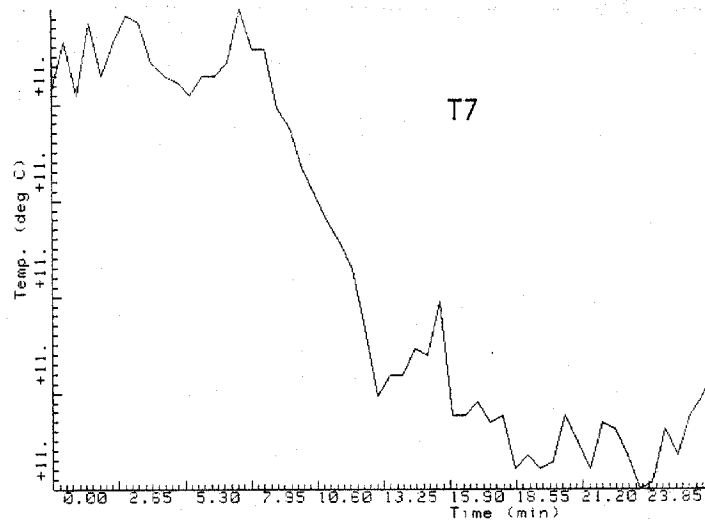
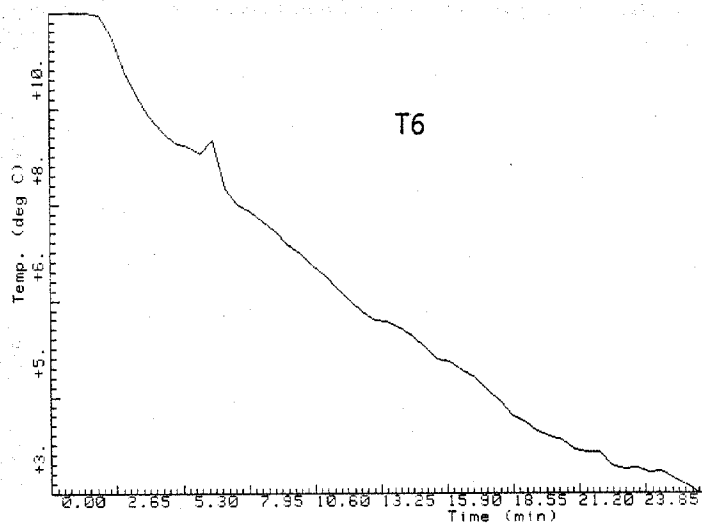


Figure A-3. TEST 6 Results

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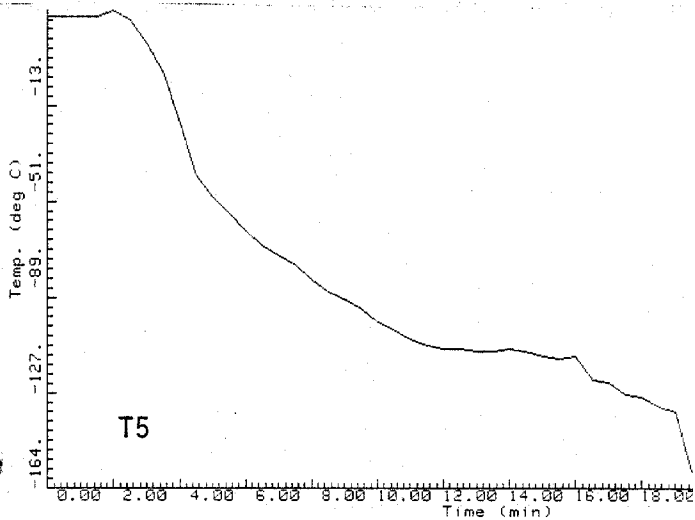
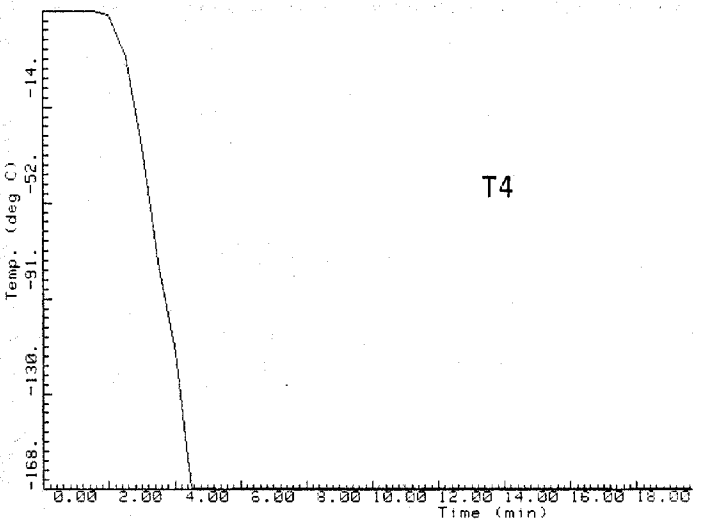
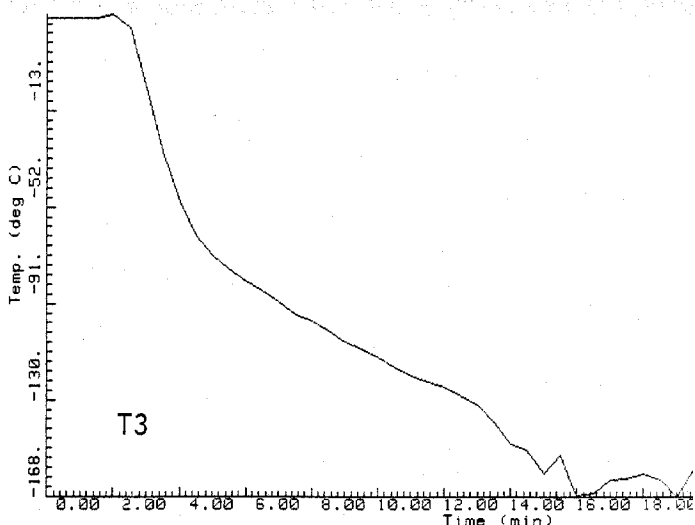
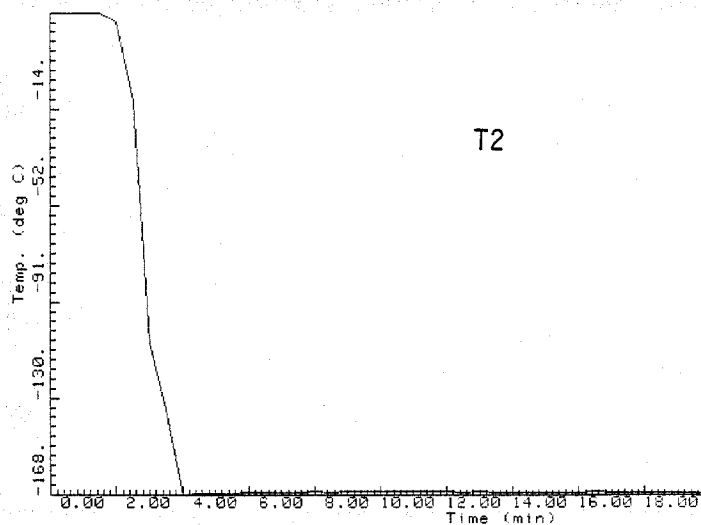
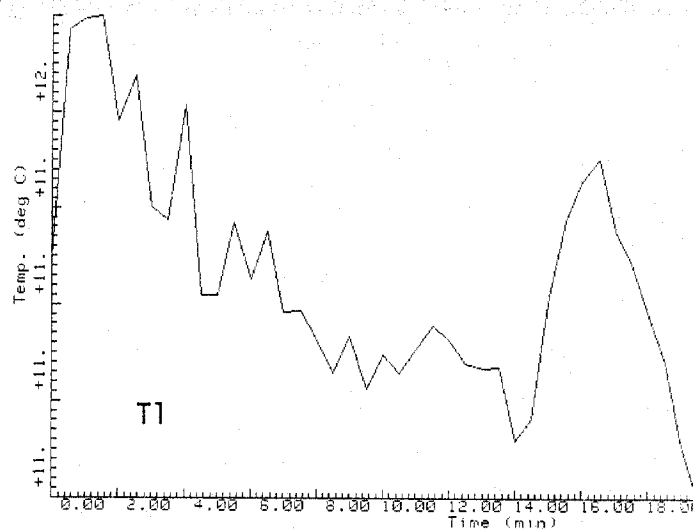
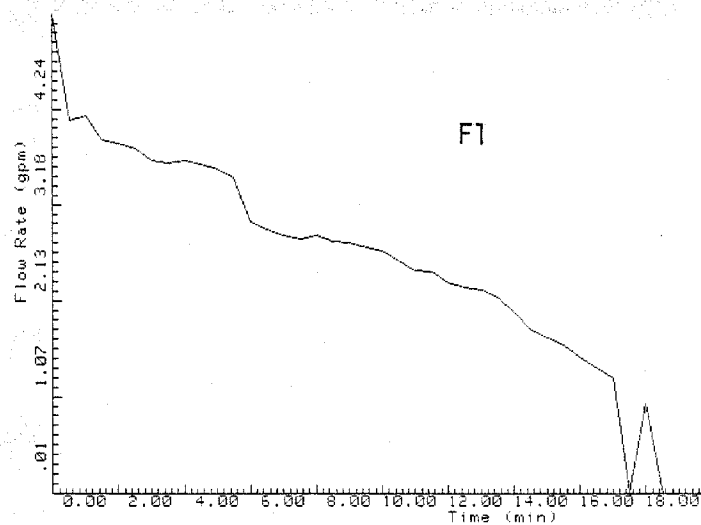
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Figure A-3. TEST 6 Results (Concluded)

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Figure A-4. TEST 4 Results

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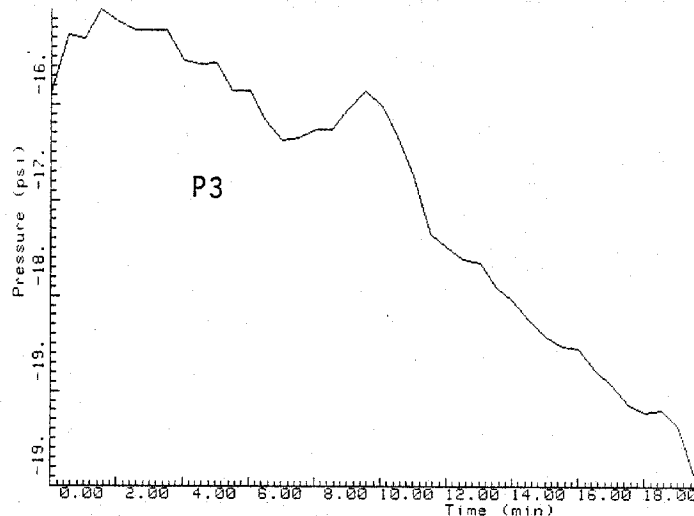
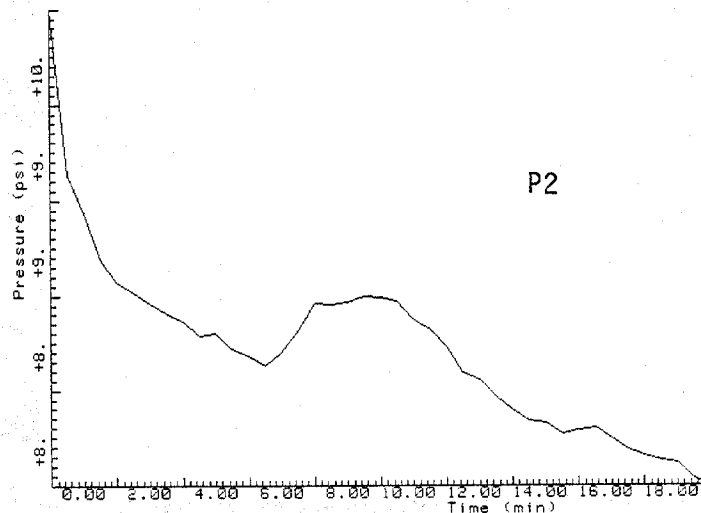
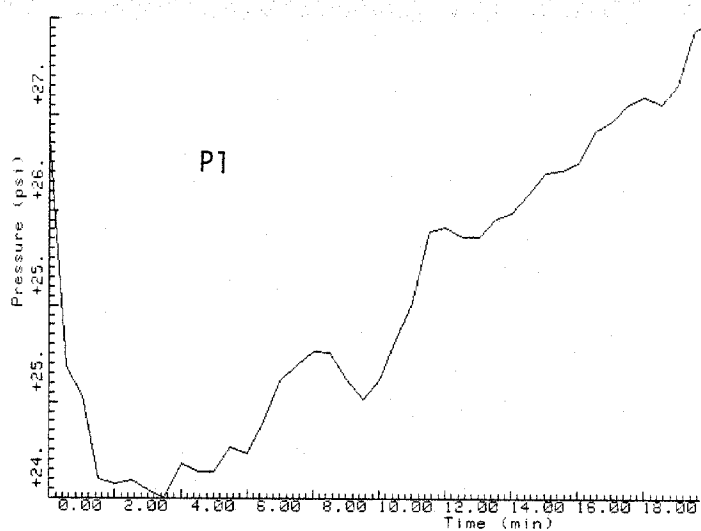
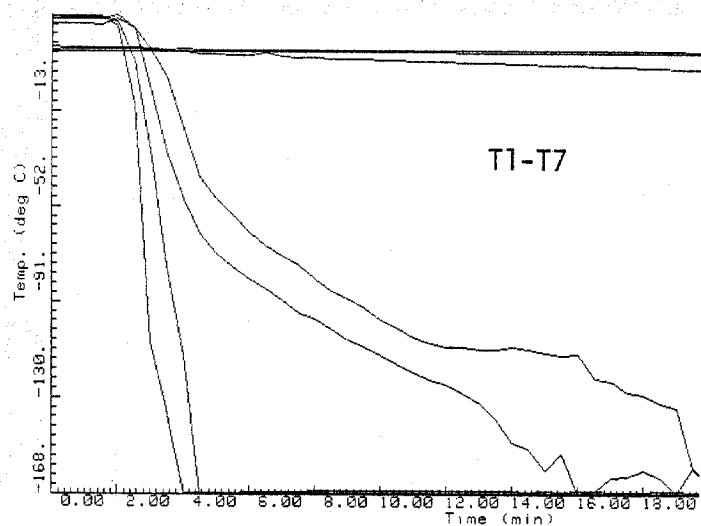
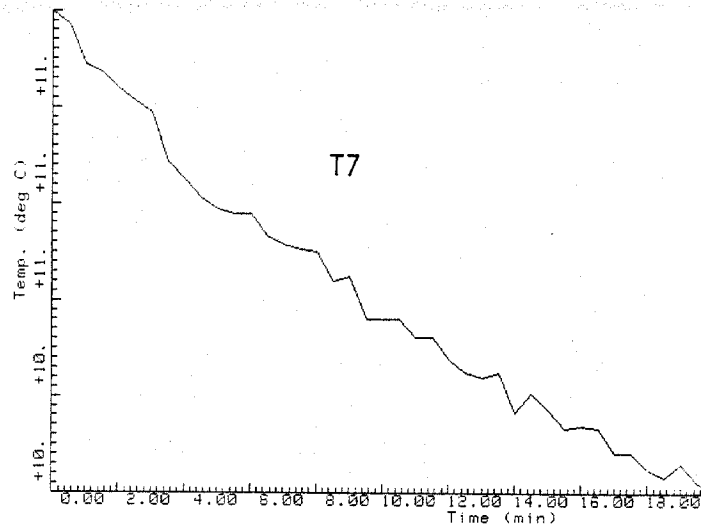
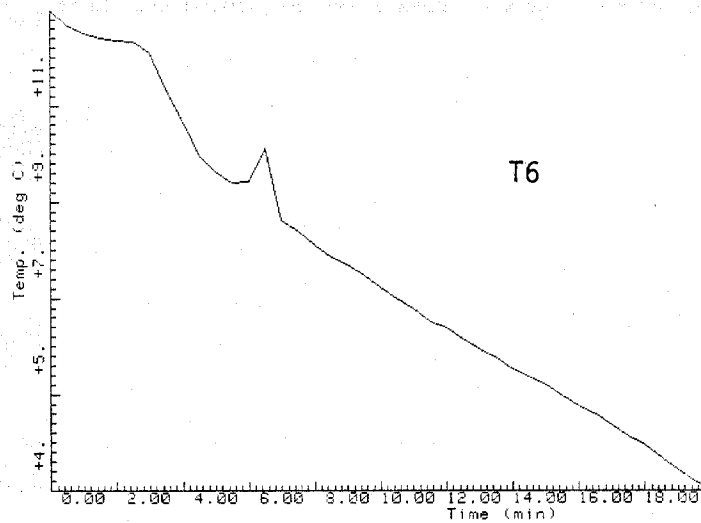


Figure A-4. TEST 4 Results (Concluded)

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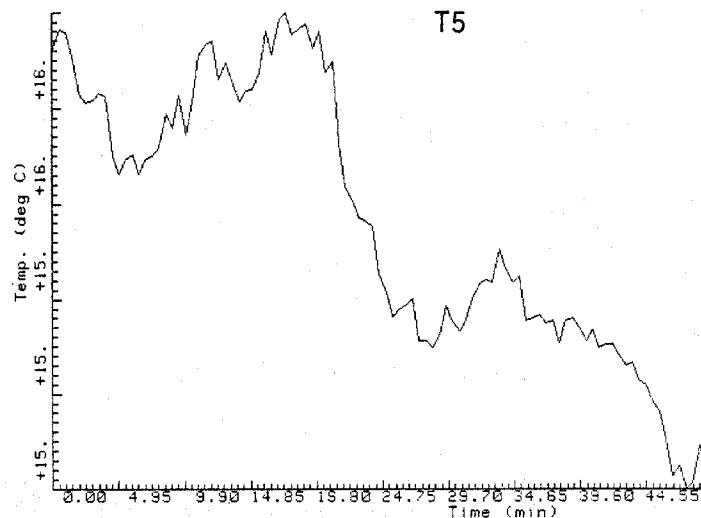
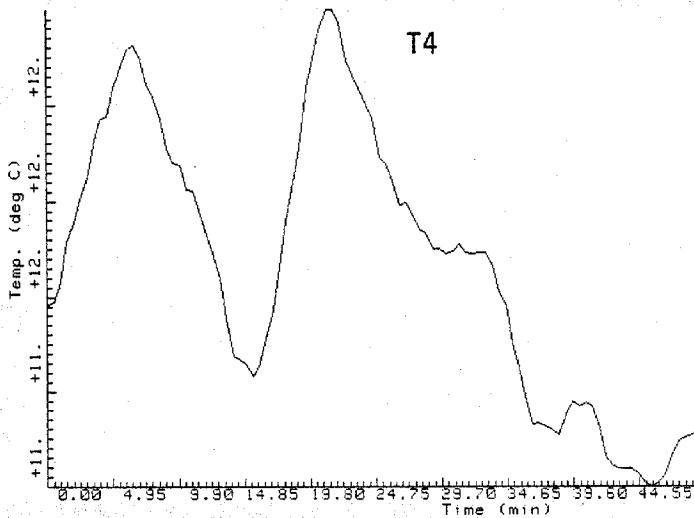
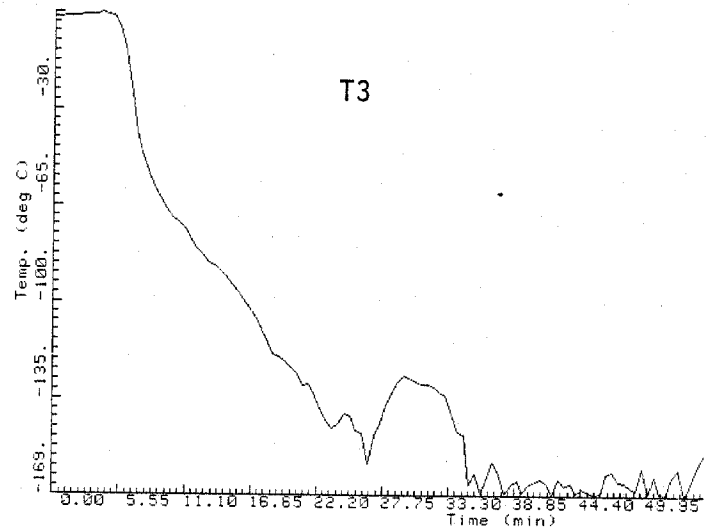
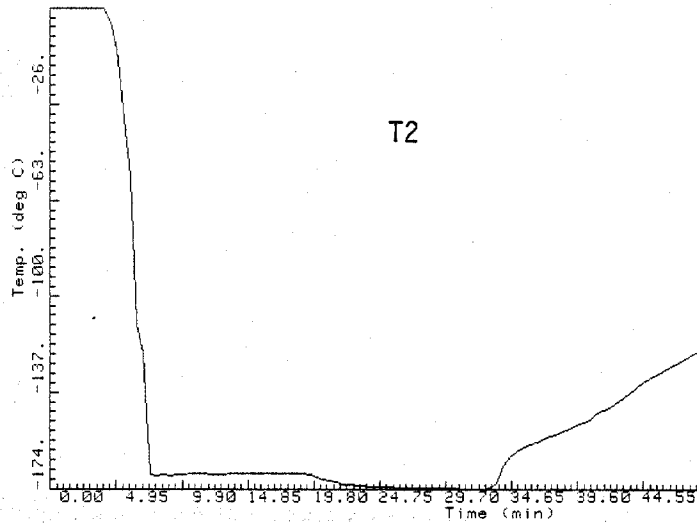
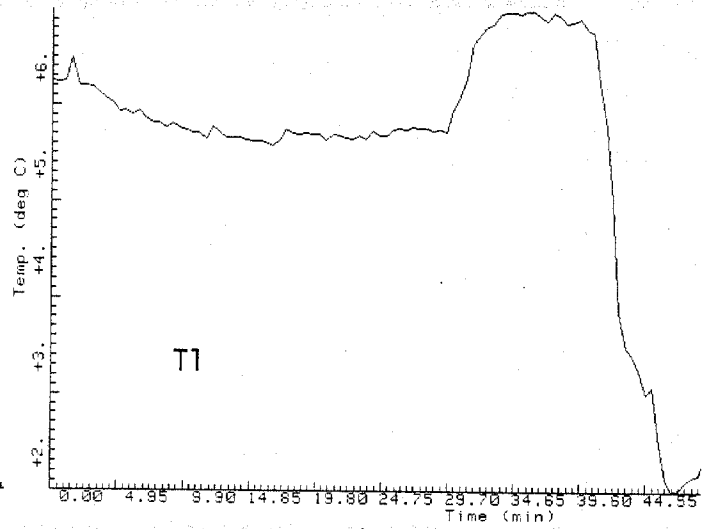
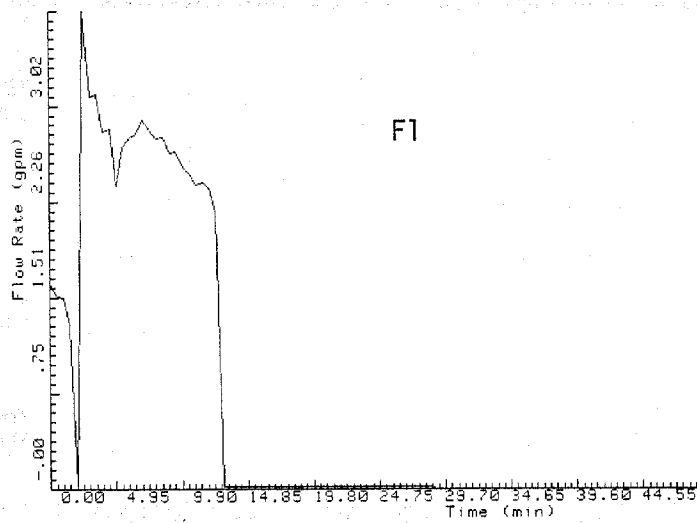


Figure A-5. TEST 11 Results

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est (Time Sensor)

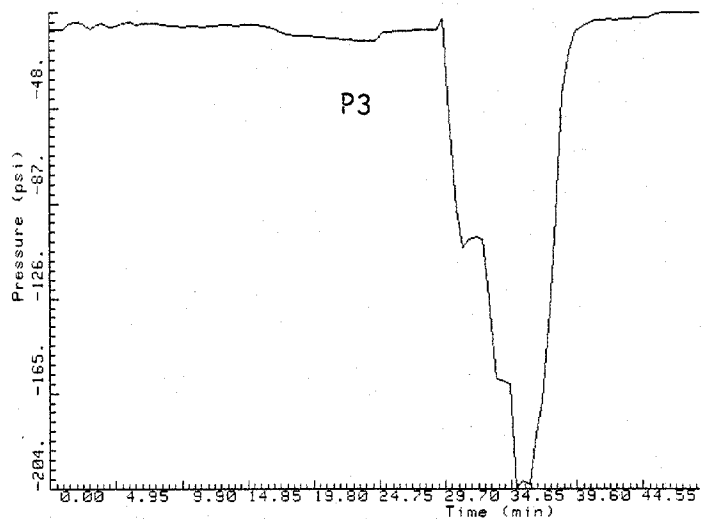
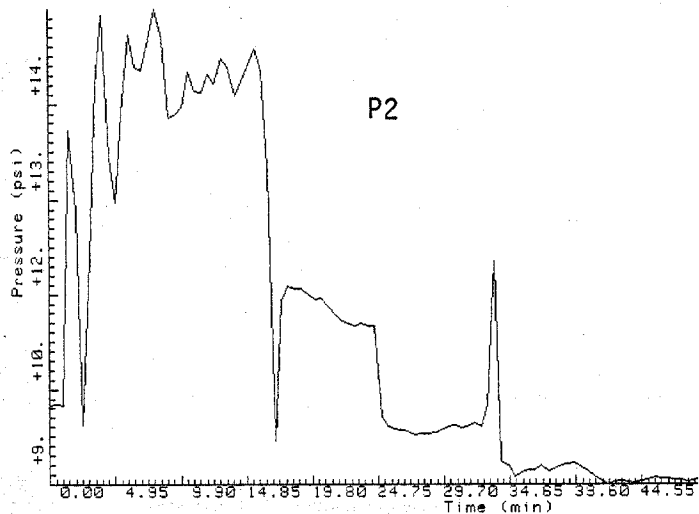
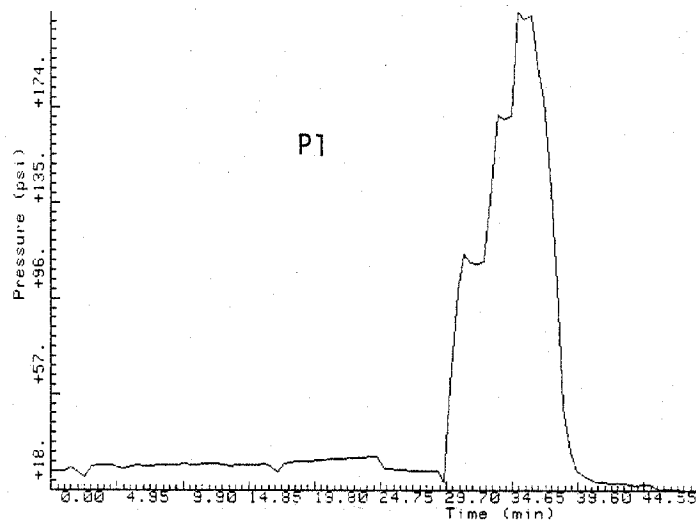
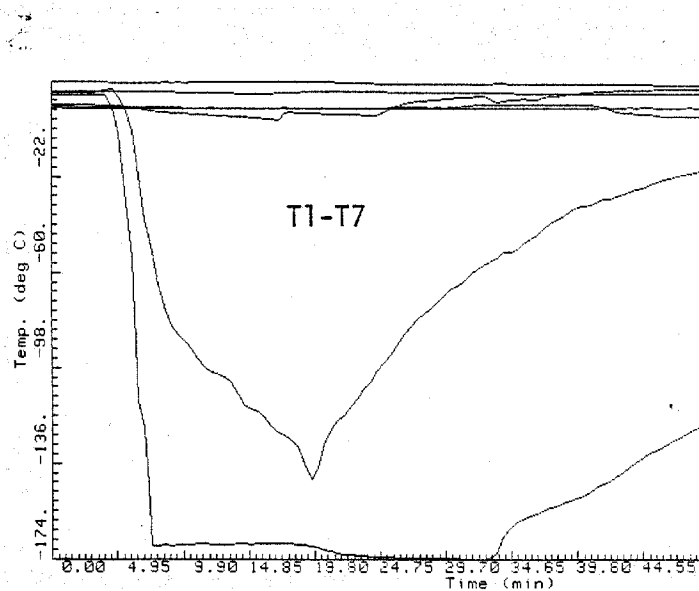
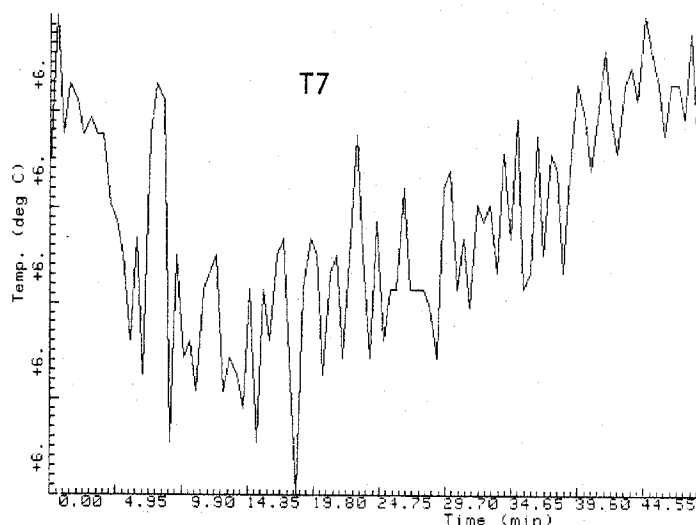
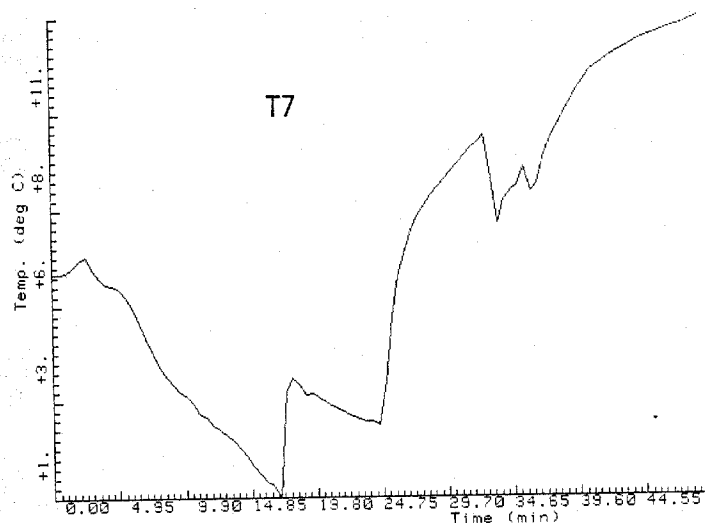
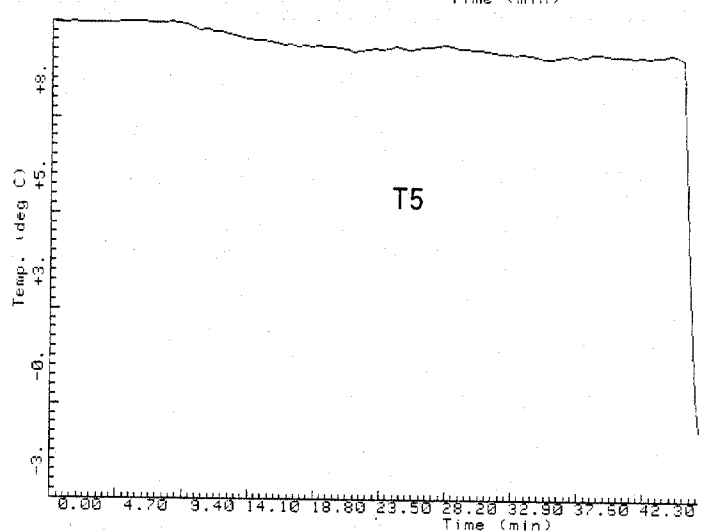
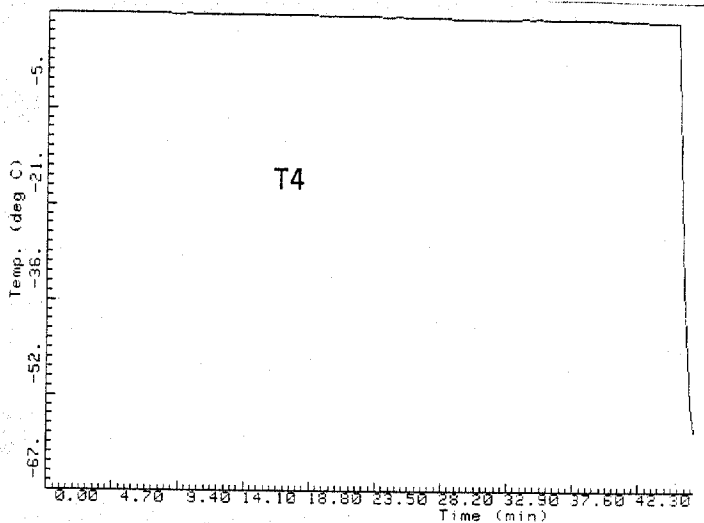
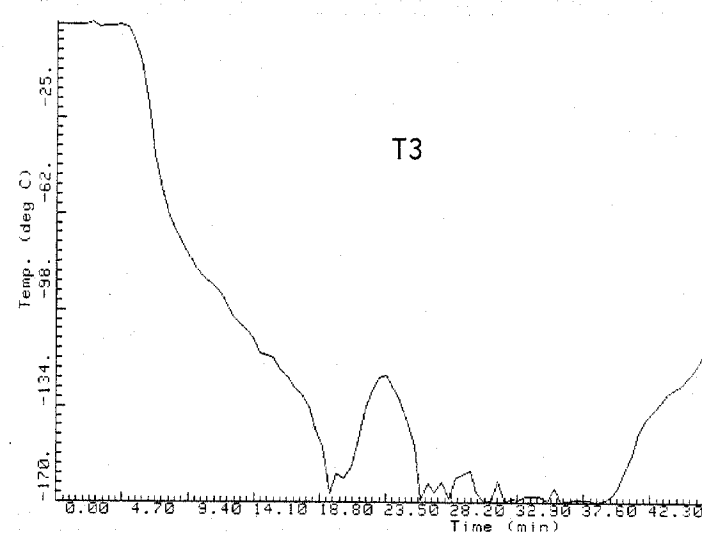
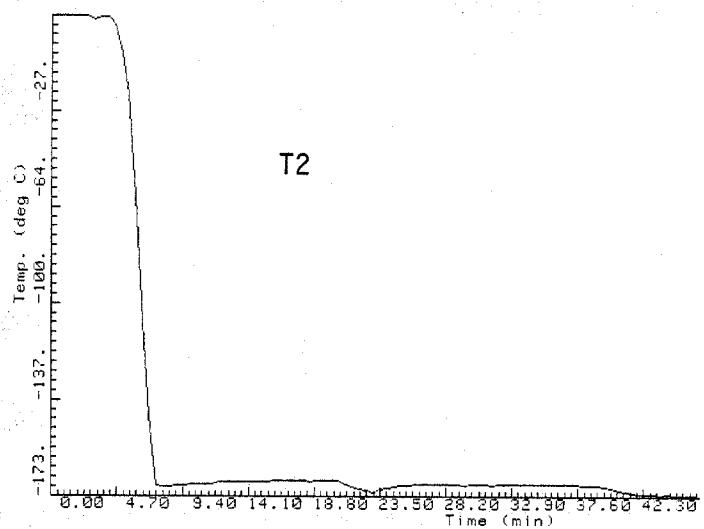
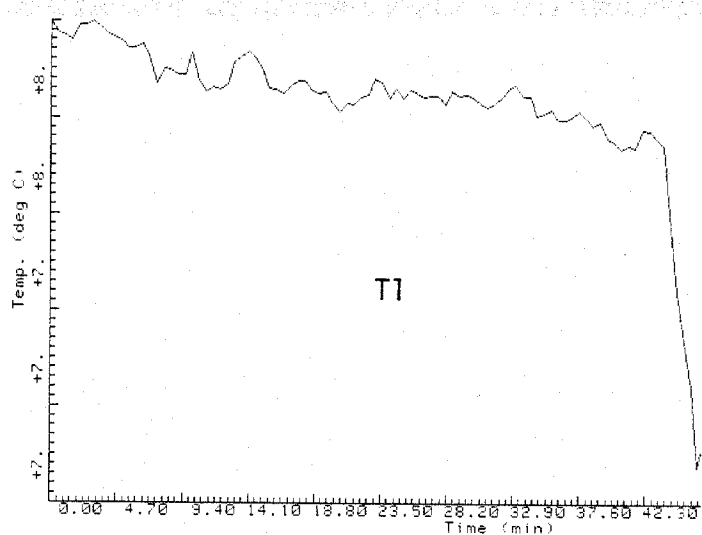
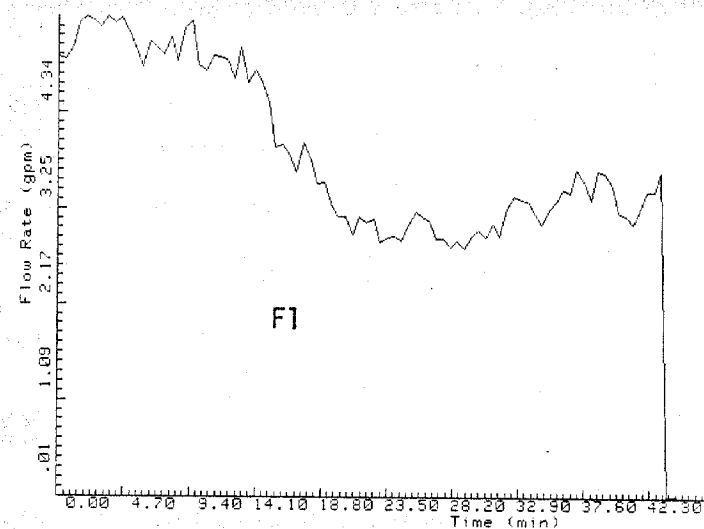


Figure A-5. TEST 11 Results (Concluded)

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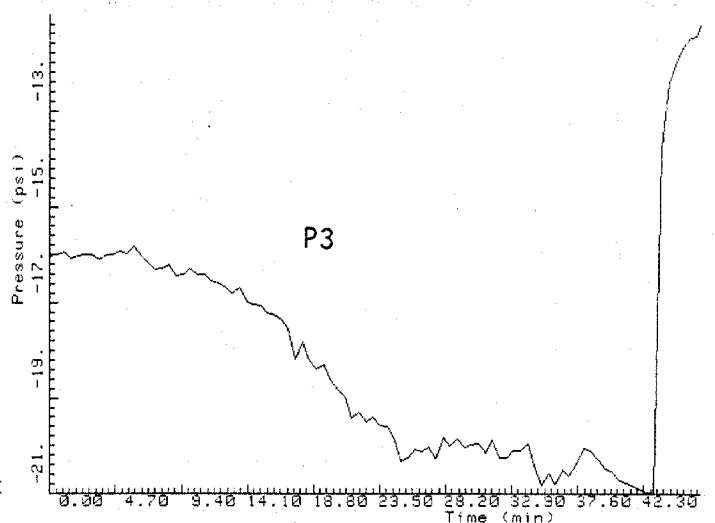
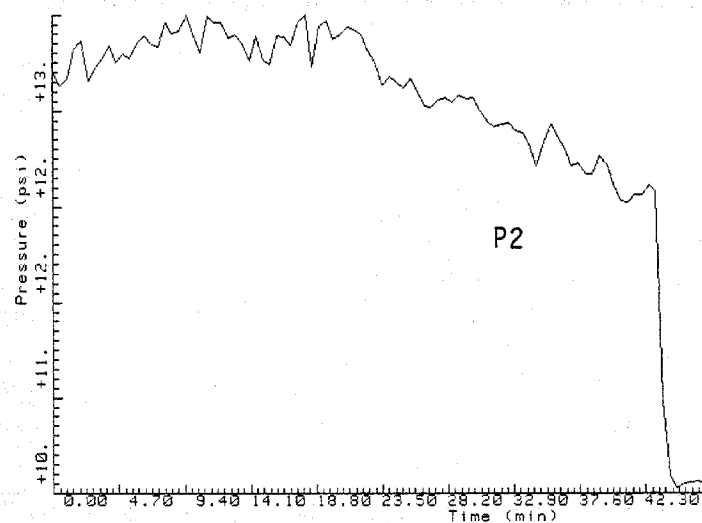
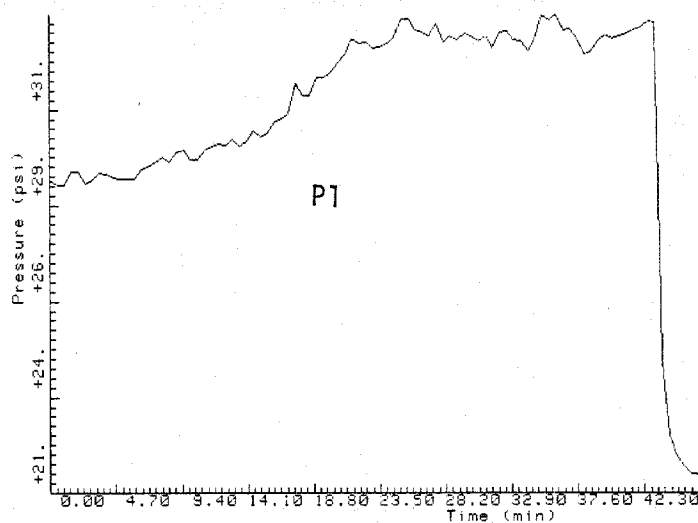
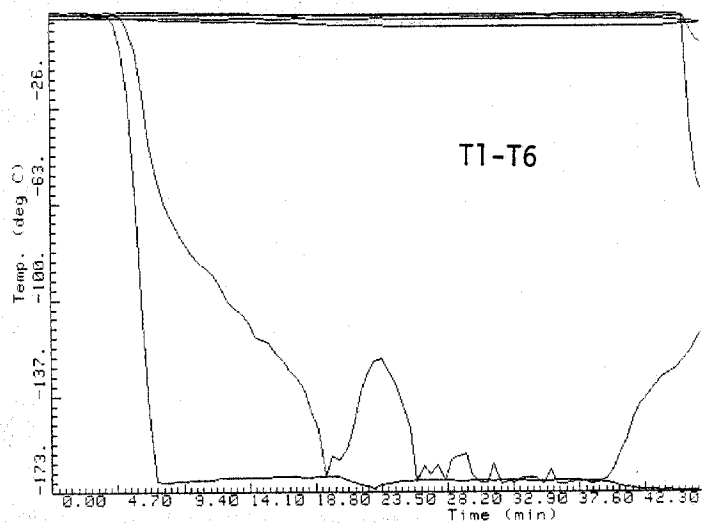
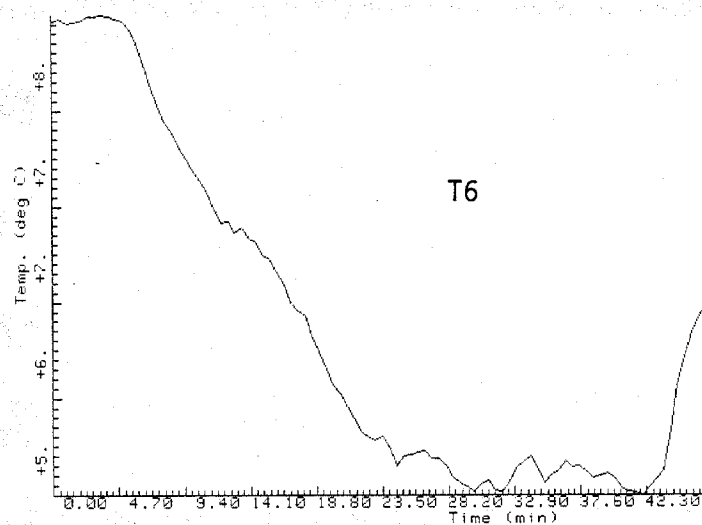
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Figure A-6. TEST 12 Results

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Figure A-6. TEST 12 Results (Concluded)

# THE BDM CORPORATION

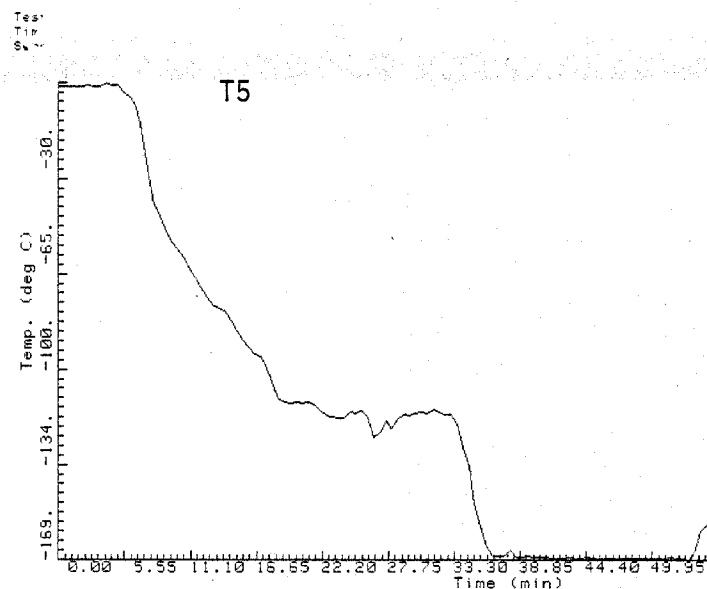
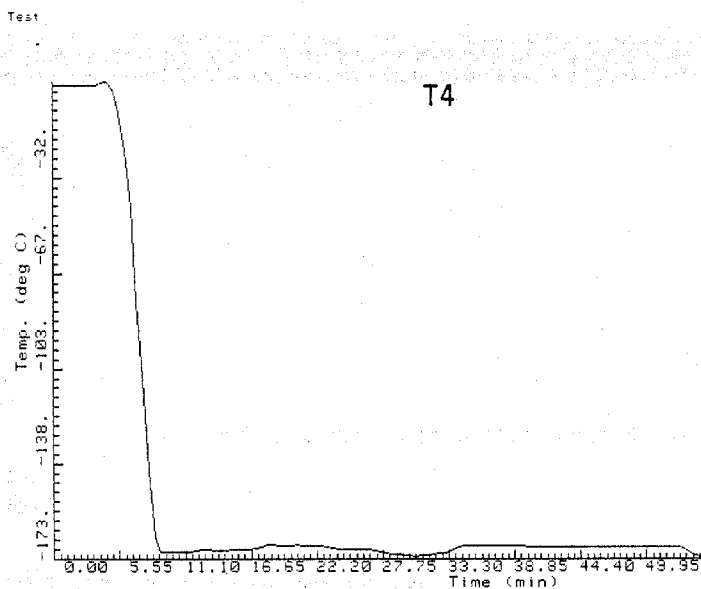
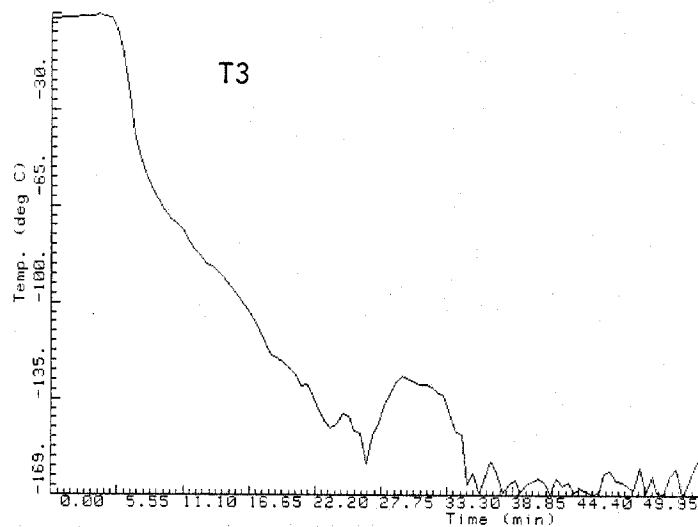
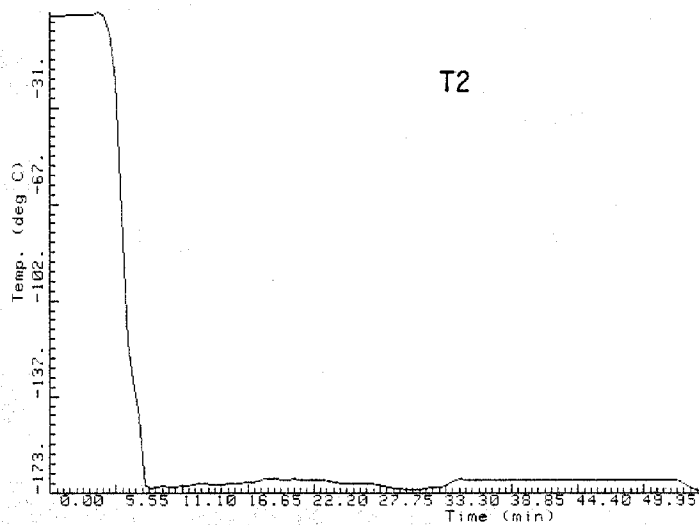
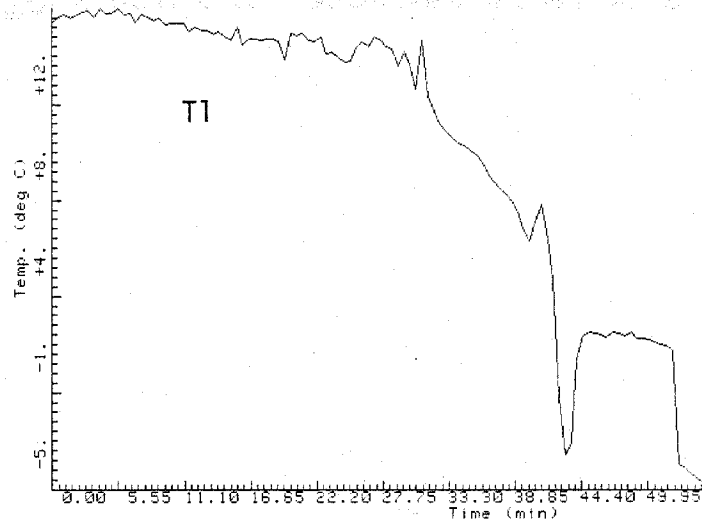
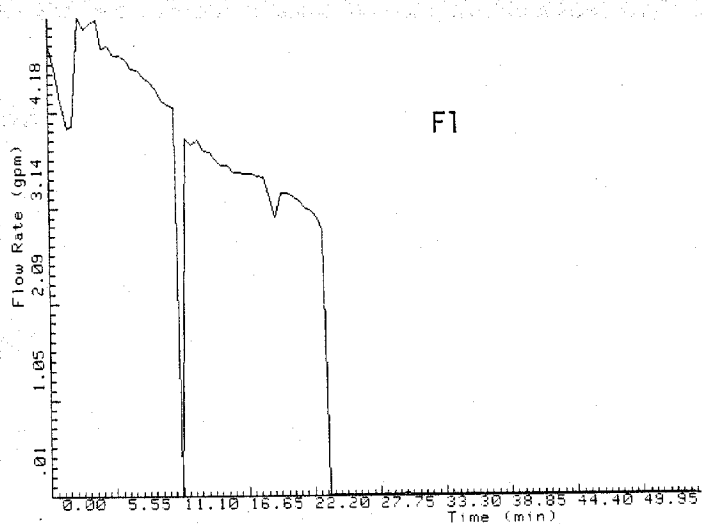


Figure A-7. Demo 2 Results

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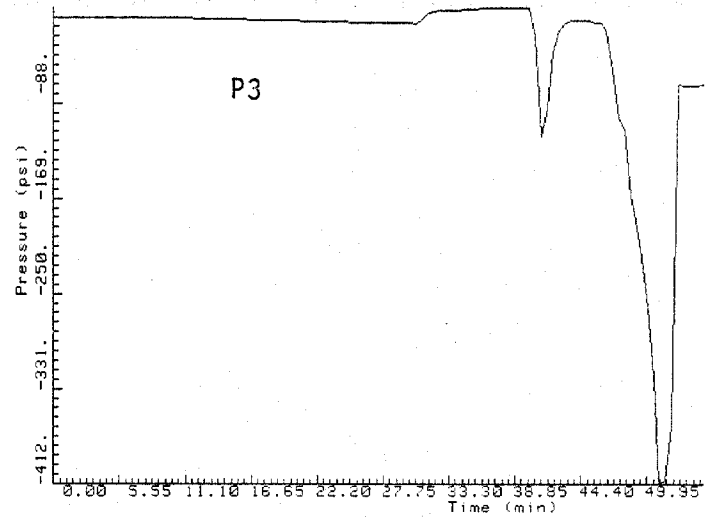
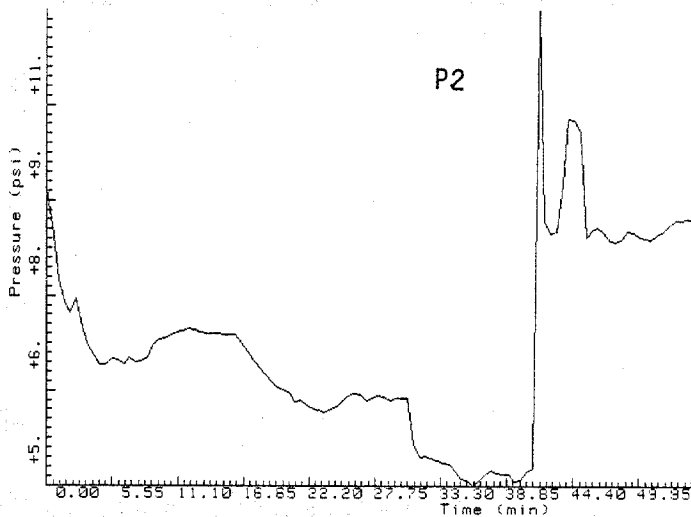
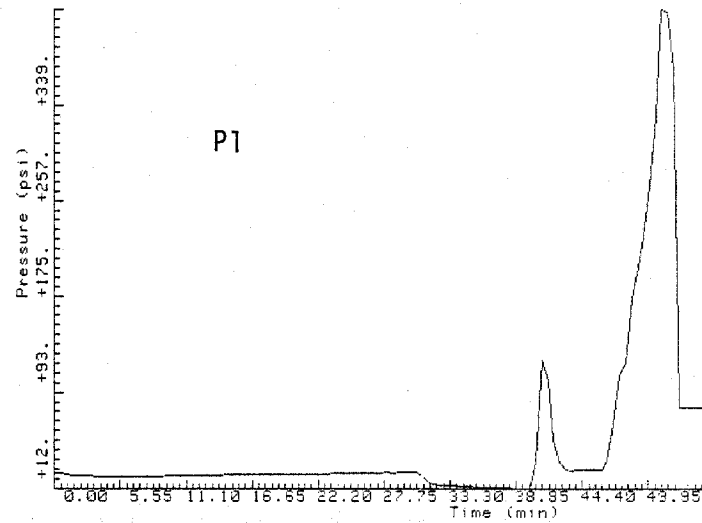
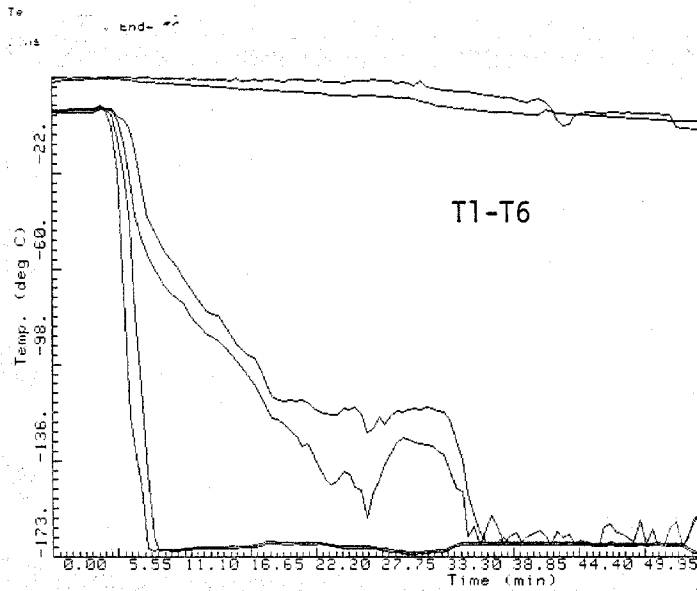
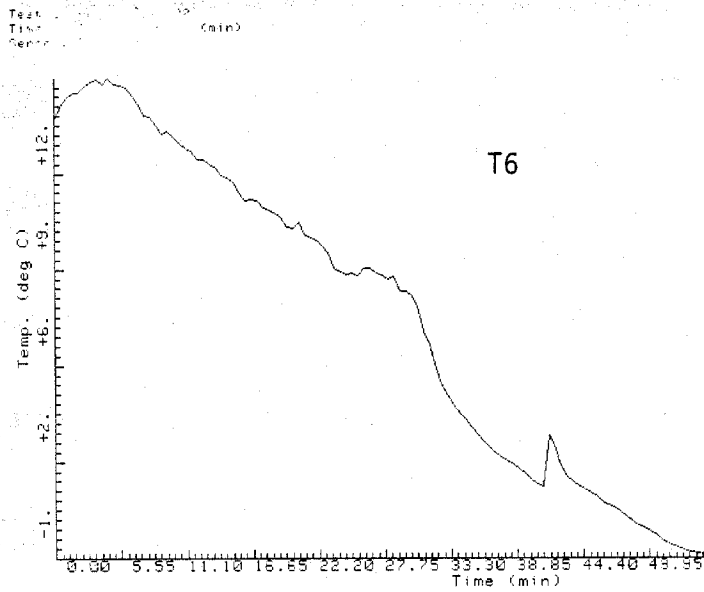


Figure A-7. Demo 2 Results (Concluded)

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The assumption was also made that the temperature differentials  $\Delta T_w$  and  $\Delta T_o$  would be the same for the model and full scale devices; therefore, dimensionless ratios (5) and (6) which contain differential temperatures and material properties would be the same for the model and full scale device. The remaining dimensionless ratios are discussed below.

Dimensionless Ratio No. (7), Reynolds Number

To scale the flow conditions or momentum (i.e., the ratio of inertia force to viscous forces) the Reynolds Numbers should be equal

$$\left( R_e \right)_m = R_e$$

$$\left( \frac{\rho_l V D}{\mu} \right)_m = \frac{\rho_l V D}{\mu} \quad \text{or} \quad \left( \frac{\rho_l G}{\mu D} \right)_m = \frac{\rho_l G}{\mu D}$$

Since the fluid properties are the same and  $D_m = D/4$

$$\frac{G_m}{D} = \frac{G}{D} ; \quad G_m = \frac{G}{4}$$

Thus the flow required in the one-quarter scale model for similarity is one-fourth that of the full scale model.

Dimensionless Ratio No. (8)

This ratio contains the convective heat transfer coefficient,  $h$ , which is the key parameter for predicting performance of the full scale device. The relation between this ratio for the model and full scale device is unknown, so this ratio must be described in terms of known quantities. For turbulent flow of fluid in a pipe, the Dittus-Boelter relation gives

$$\frac{hD}{k_l} = 0.023 R_e^{0.8} P_r^{0.3}$$

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We have already set conditions for equal Reynolds numbers and if we assume the same fluid, then the Prandtl numbers will be equal. Therefore, its right side of the equation is the same for model and full scale and we can write

$$\left( \frac{hD}{k} \right)_m = \frac{hD}{k}$$

$$\left( h_m \right) \frac{D}{4} = hD$$

$$h_m = 4h$$

Thus, if the Reynolds and Prandtl numbers are the same for model and full scale device and the flow is turbulent, the heat transfer coefficient for the model should be four times that for a similar full scale device.

### Dimensionless Ratio No. (9)

If the ratio of pressure to inertia forces to be held constant then

$$\left( \frac{\rho_e V^2}{\Delta p} \right)_m = \frac{\rho_e V^2}{\Delta p}$$

$$\left( \frac{\rho_d G^2}{\Delta p D^4} \right)_m = \frac{\rho_d G^2}{\Delta p D^4}$$

$$\frac{(G/4)^2}{\Delta p_m \left( \frac{D}{4} \right)^4} = \frac{G^2}{\Delta p D^4}$$

$$\Delta p_m = 16 \Delta p$$

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However, the pressure differential across the system only manifests itself in producing a volumetric flow rate. It is this flow rate which determines the heat transfer characteristics from the fluid to the wall of the test section and therefore the time required for freezing. The only other way in which pressure affects the test is in forcing the solid plug out of the test section or in changing the physical properties of the flowing mixture.

### Dimensionless Ratio No. (10)

This ratio will be obviously similar with the one-quarter scale geometry selected.

$$\left(\frac{L}{D}\right)_m = \frac{L}{D}$$

$$\frac{L/4}{D/4} = \frac{L}{D}$$

### Dimensionless Ratios (11) and (12)

Analysis of these ratios indicate that for these ratios to be equal between the model and full scale device, events must take place faster in the scale model.

Generally, the similarity study for an unobstructed tube shows that scaling the diameter, lengths, and flow of the DSD by one-fourth gives flow similarity, and also that events will take place faster in the scale model.

### 3. Test Section and Layout Design

#### Test Section

Following the similarity study which indicated a scale factor of one-fourth, the design of the physical model was developed. For the test section, which represents the model of the DSD, a 2-inch stainless steel tube with two helical rows of deflector blades was selected. Deflector blades were spaced longitudinally along the length of the 2-inch oil tube at a distance approximately equal to the length of a deflector blade. This simulates the actual DSD by allowing space along

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the tube wall for the retracted or stored blade position. However, for the model, the blades were fixed in a deployed portion of 45° since development of the blade deployment was not part of this program.

A test section length of 7.5 ft was selected based on one-fourth of the nominal length of 30 ft for a typical well casing.

A 6-inch tube was used to enclose the 2-inch oil tube and provide the annular space for the flow of liquid nitrogen. The 6-inch tubes used had been previously fabricated for a different project and contained bellows and adjustment rods which would not be required for the DSD. Bolted flanges were used for all test section connections. Types 304 and 347 stainless steel were used for all test system components which would be exposed to cryogenic temperatures.

Figure 5 depicts a sketch of the basic design of the test section. Note that figure 5 shows two test sections connected in-line to facilitate investigation of the effects of test section length on freezing performance.

Details of the deflector blades and the 2-inch oil pipe are shown in figure 6. One hundred and fifteen slots were machined in the oil pipe for each test section to position and orient the blades, then all blades and flanges were welded and the test section pressure-tested to 700 psig. The mixer section shown in figure 7 was incorporated at the test section inlet to allow for testing mixtures of oil, gaseous nitrogen, and water. However, water mixtures were not tested since the addition of water would expedite freezing; therefore, oil or oil/gas mixtures represented worst-case fluids for the test program.

All portions of the test layout which would be pressurized during the final phase of each test to determine the ability of the frozen oil plug to withstand design pressure were structurally analyzed in accordance with ANSI standards.

The capabilities of the deflector blade to hold the frozen plug in place were investigated for the model and for a full scale device. A stress analysis was conducted to determine the pressure required to fail the deflector blades in shear, assuming the plug load was distributed

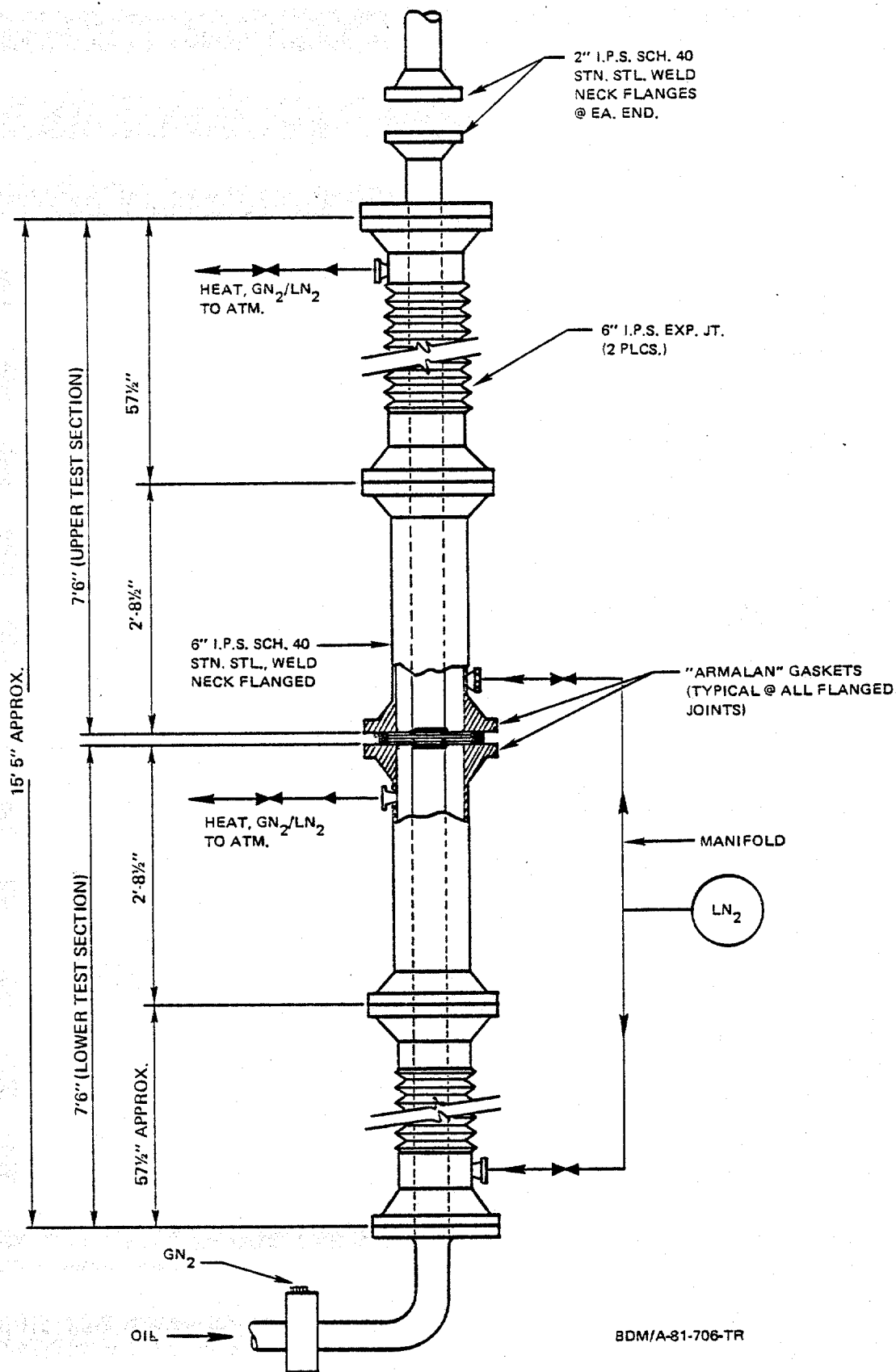
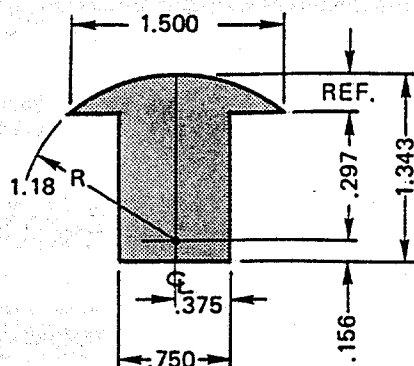


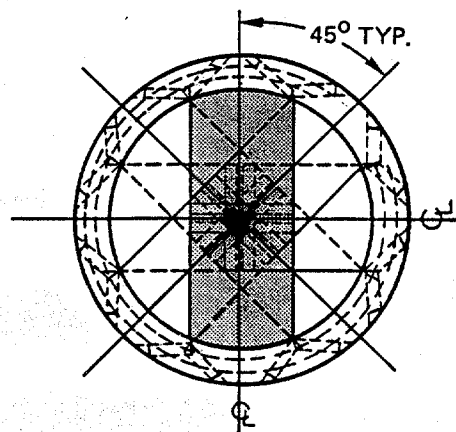
Figure 5. Sketch of DSD Model Test Section

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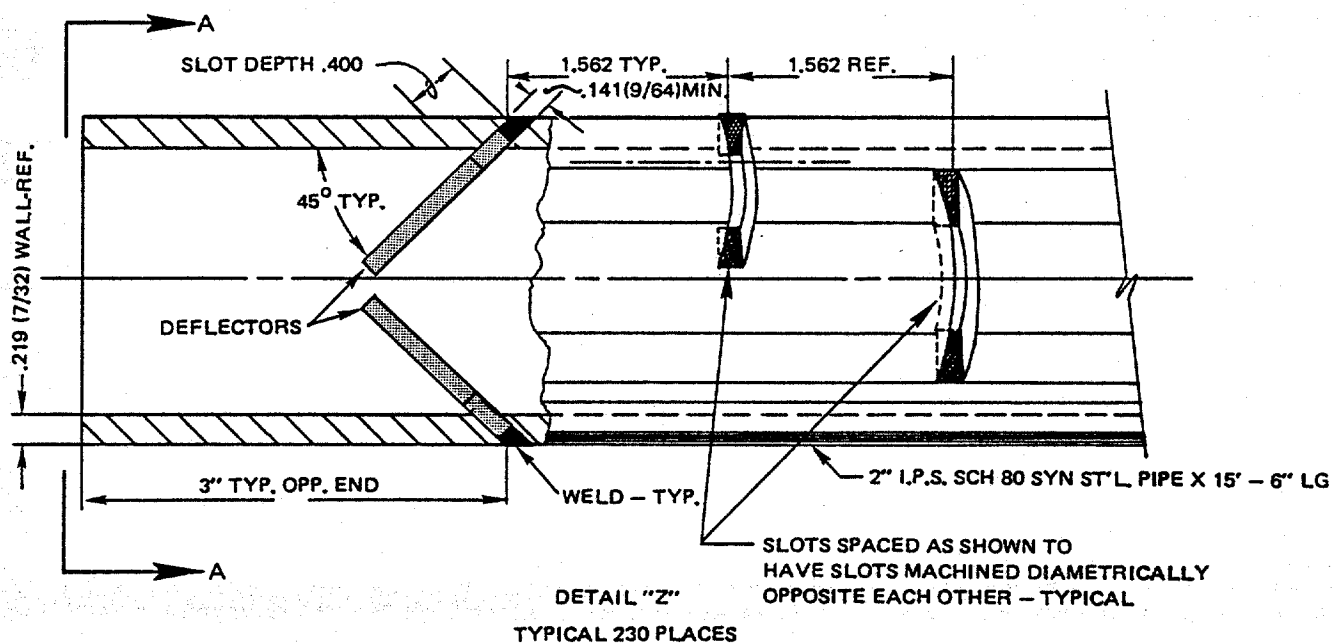


## DEFLECTOR

MAT'L: (.135) TYPE 304 STN. ST'L - 2B FINISH  
230 REQ'D.



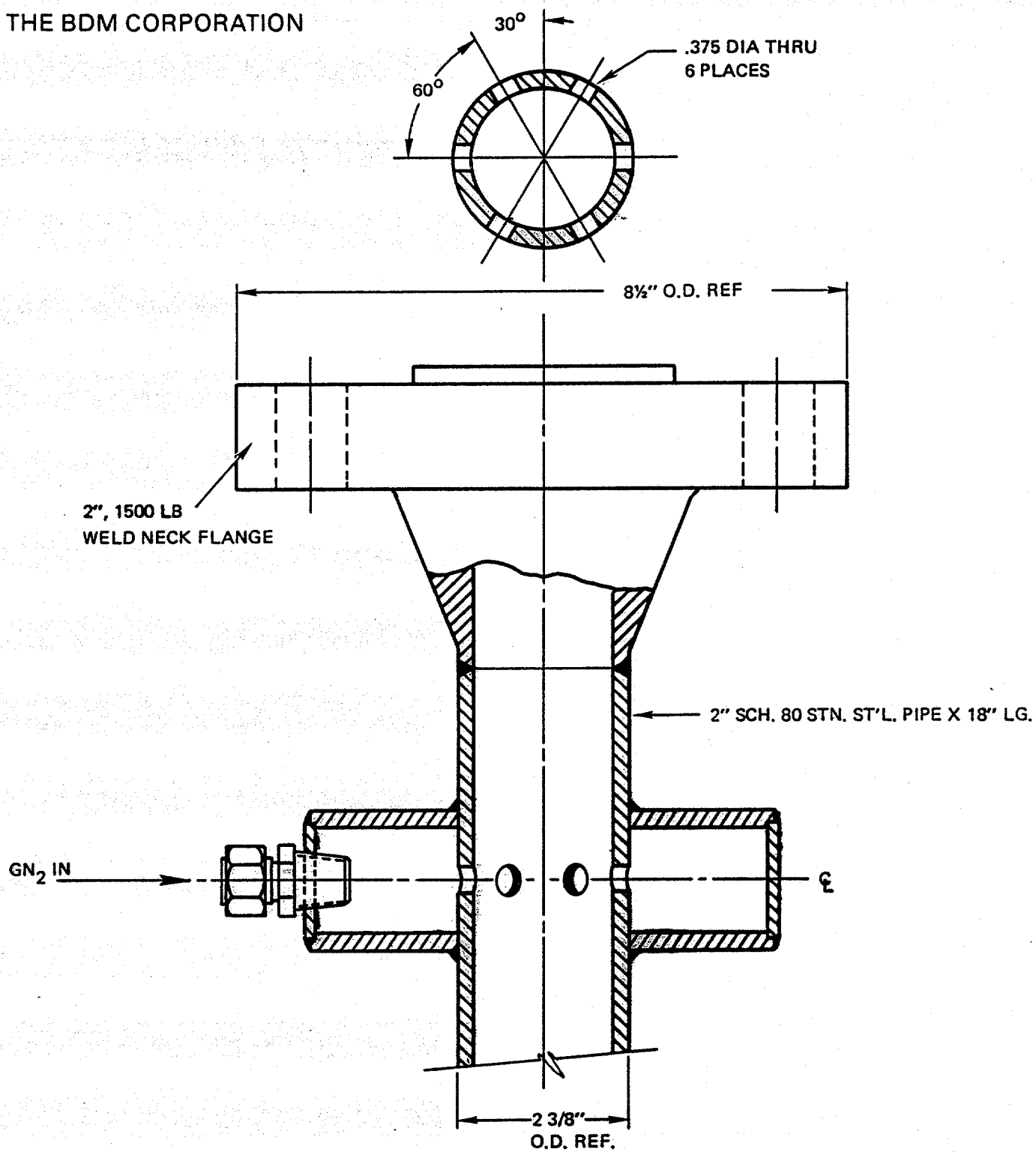
VIEW A-A



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Figure 6. Details of DSD Model Oil Pipe and Flow Deflector

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Figure 7. Mixer Section

over 230 blades and neglecting the friction forces between the plug and pipe wall. This analysis showed the deflector blades would resist a pressure on the oil plug of approximately 100,000 psi for the model and 39,000 psi for the full scale device.

These results indicate that the DSD design concept would easily accomodate actual pressure conditions which might be encountered. It is recommended that further testing be conducted to determine the mode shape of the blades when the plug is pressurized. This would allow a more refined stress analysis which would consider both shear and bending loads on the blades.

#### Test Layout

Ancillary equipment for the test section consisted of oil supply and return tanks, oil transfer pumps, a compressed air supply for producing the desired oil flow, a compressed gaseous nitrogen supply for providing a gaseous mixture of test fluid and for operating pressure regulators, and a supply of liquid nitorgen. High pressure stainless steel tubing was used for all oil,  $GN_2$ , and  $LN_2$  flow circuits. Figures 8 and 9 show the schematic layout for the test assembly. Instrumentation for the system consisted of pressure, temperature, and flow sensors which are described below.

#### 4. Instrumentation/Data Acquisition System

The following parameters were monitored and recorded during testing using the pressure, temperature, and flow transducers, and the data acquisition system shown in figure 10:

- (1) Oil flow (F1)\*
- (2) Oil pressure at test section inlet (P1)\*
- (3) Oil pressure at test section outlet (P2)\*
- (4) Oil pressure drop across test section ( $P3=P2-P1$ )\*
- (5) Oil temperatures at test section inlet (T1)\*
- (6) Cryogen temperature at inlet of lower test section (T2)\*
- (7) Cryogen temperature at outlet of lower test section (T3)\*
- (8) Cryogen temperature at inlet of upper test section (T4)\*
- (9) Cryogen temperatures at outlet of upper test section (T5)\*

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\*Locations are shown in figures 8 and 9.

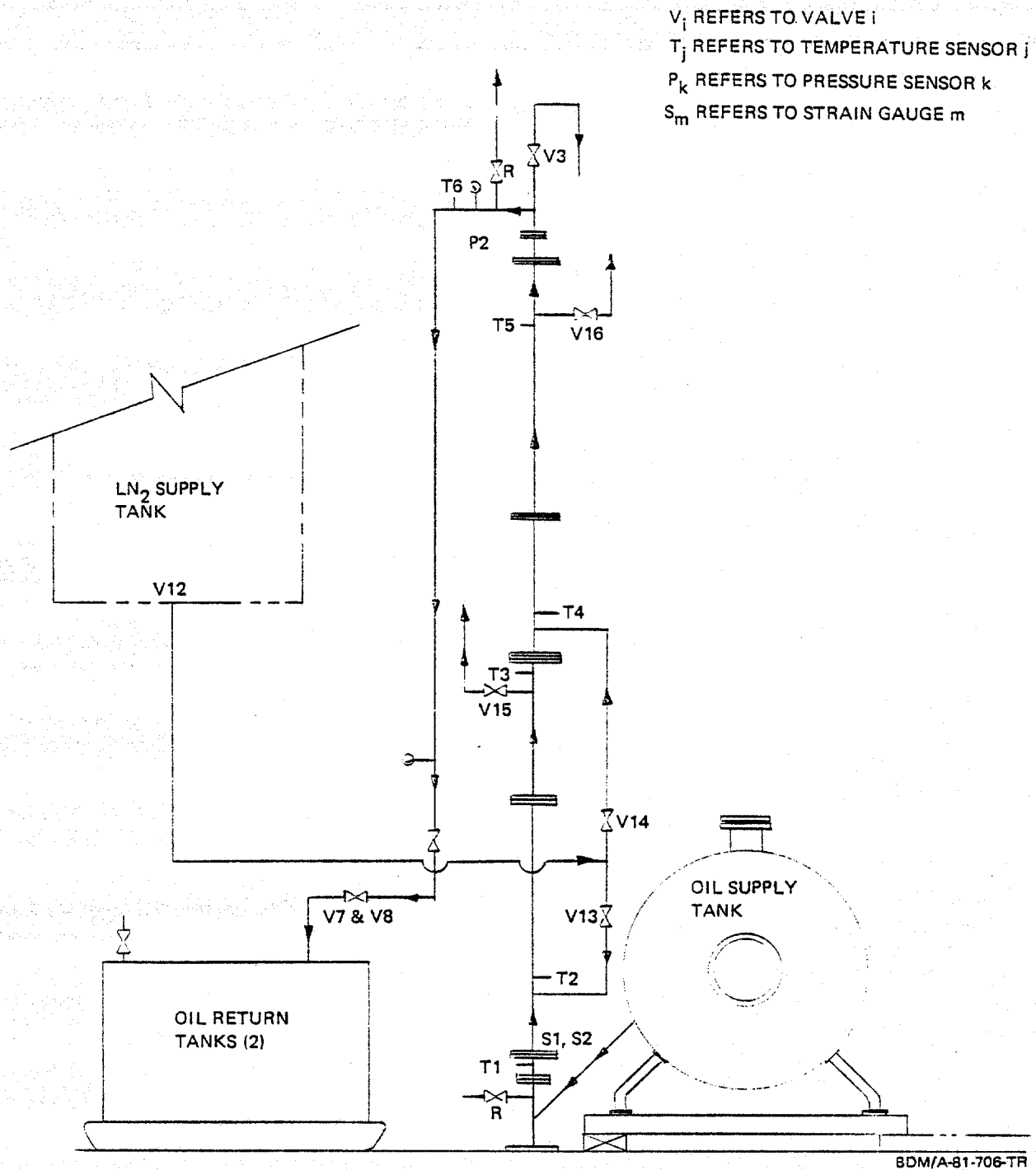


Figure 8. Test Layout Schematic - Elevation View

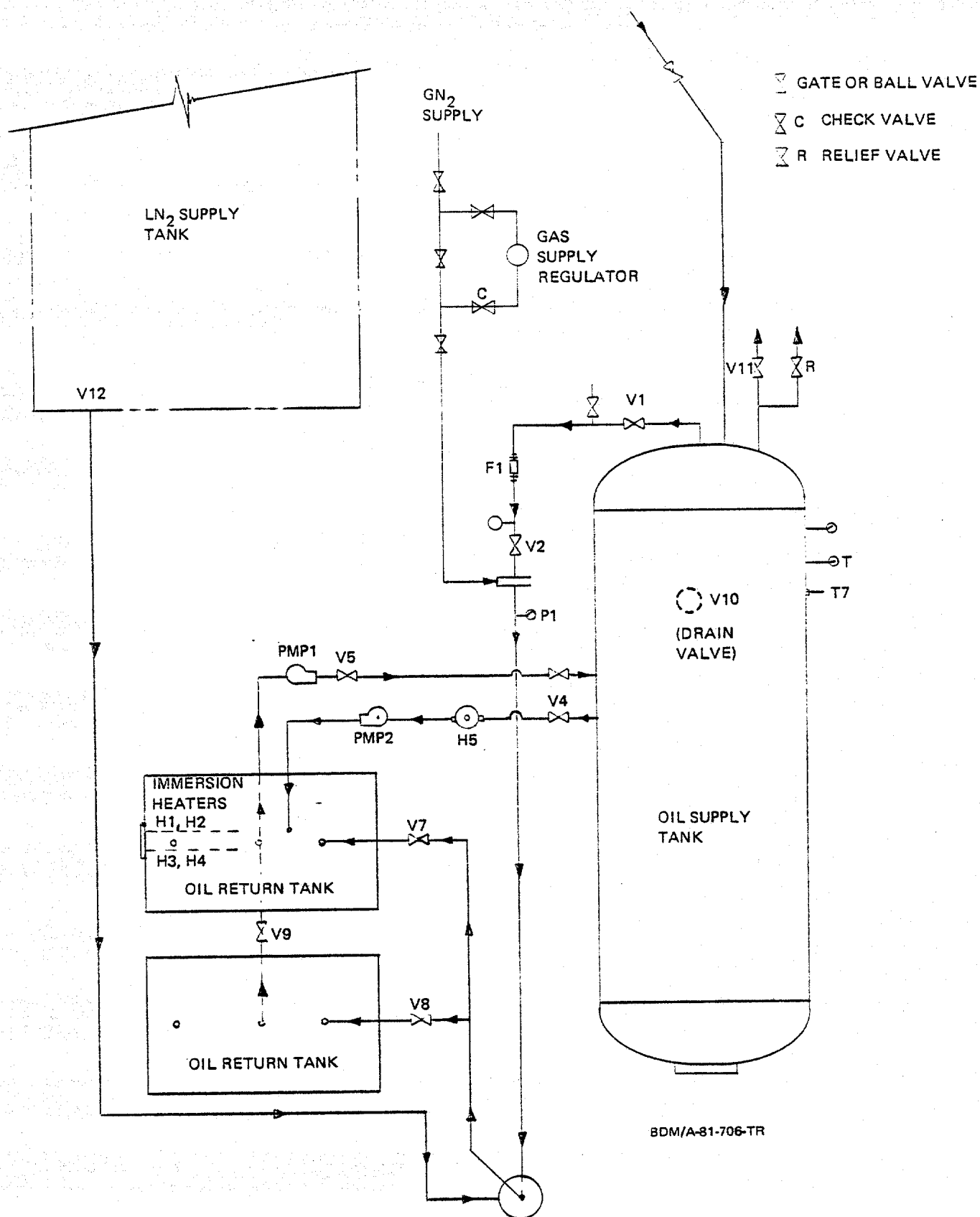
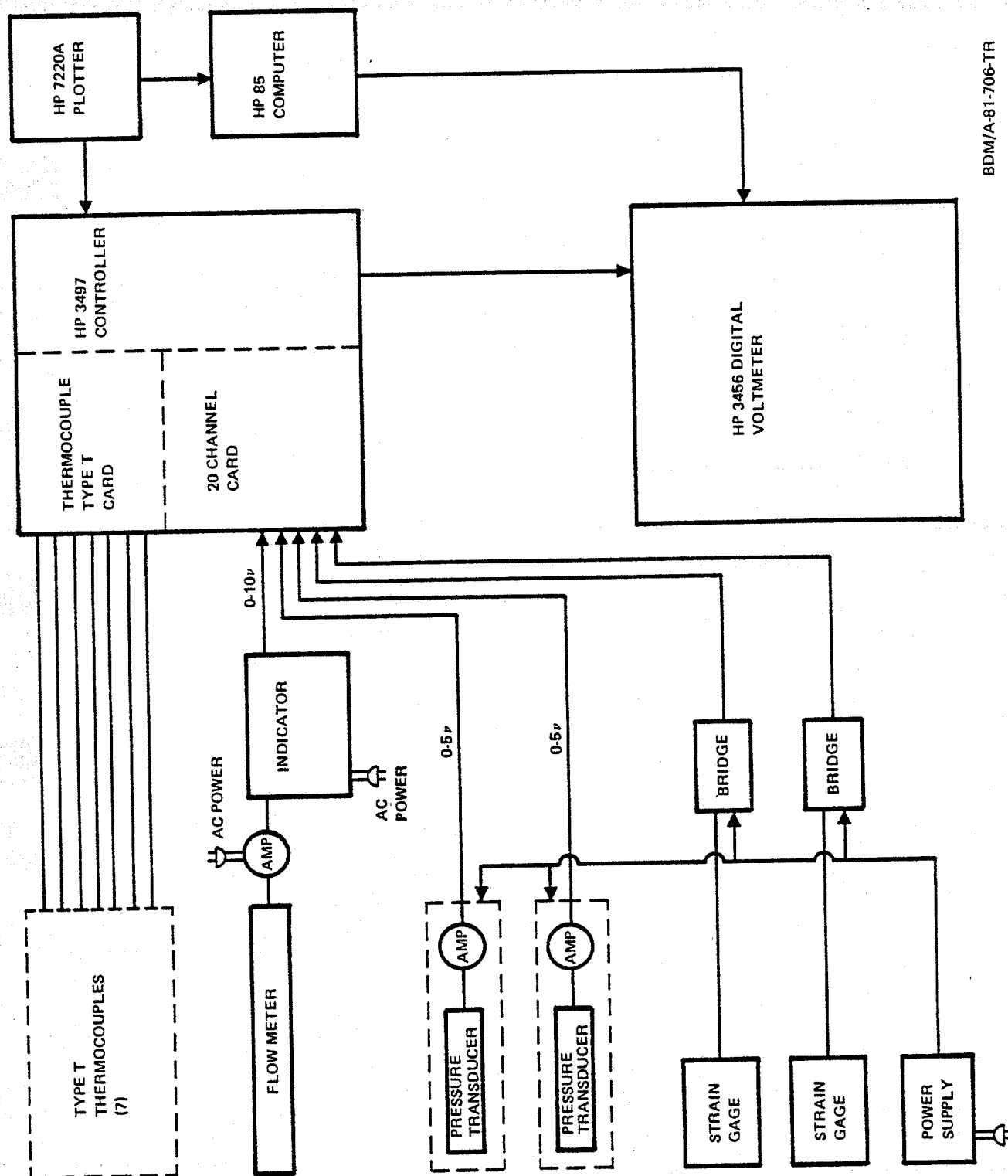


Figure 9. Test Layout Schematic - Plan View



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Figure 10. Instrumentation/Data Acquisition System

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(10) Oil temperatures at outlet of upper test section (T6)\*

(11) Oil temperature in supply tank (T7).\*

Other instrumentation consisted of the following visual readout gauges for monitoring and setting test conditions:

- (1) Air supply pressure
- (2) Gaseous Nitrogen supply pressure
- (3) Air pressure in oil supply tank
- (4)  $\text{GN}_2$  pressure for frozen plug pressure tests
- (5)  $\text{GN}_2$  pressure for remote oil flow valve
- (6) Oil supply tank temperature.

All visual readout gauges were standard Ashcroft, Model 137755, bourdon tube gauges. Transducers and data acquisition components were as follows:

Pressure transducers: Statham Instruments, Inc., Part No. PA418-1M-7, Range 0 to 1000 psia, Strain gauge type.

Temperature Sensors: ANSI Type T Thermocouple (Copper/Constantan) Range -300 to 750°F, 1/8 NPT Compression fitting mount.

Flowmeter: Flow Technology, Inc., Turbine Type, Part No. FT-16NLB, Serial No. 1601767, Calibrated over range of 3 to 20 GMP.

Strain Gauges: BLH Electronics Co., Special Purpose Cryogenic Type, Part No. FSM-25-35-59, Range -452 to 600°F with compensation, Low Temperature Adhesive PLD-700.

It should be noted that measurement of strain in the deflector blades was planned, but not implemented. The special low-temperature strain gauges were ordered, strain measurement details were worked out (including temperature compensation techniques), and the data acquisition system developed to include strain measurement and recording. However, the strain gauges were inadvertently routed to the wrong building and while attempting to locate them, the decision was made to proceed with the assembly of the test section and either disassemble and install strain gauges later or perform a structural analysis of the deflector blade stress levels. A stress analysis was eventually conducted which demonstrated that the deflector blade concept would restrain a frozen oil plug for oil pressures of 39000 psi in a full scale DSD.

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The data Acquisition/Display system consisted of the following major components:

Computer: HP-85

Controller: HP3497A

Digital Voltmeter: HP3456A

Recorder: HP7132A

Plotter: HP7225A

Software was developed for recording and displaying flow, temperature, pressure, strain, and time measurement and for generating plots of sensor measurements versus time. Plots of test results are included in appendix A.

### 5. Testing

Eleven tests were conducted on an intermittent basis between November 1981 and February 1982. Five hundred gallons of crude oil with specific gravity of 0.83 (39° API) were obtained directly from a refinery in northwest New Mexico and used for all tests.

Testing was accomplished using one and two sections and fluids consisting of pure crude oil and mixtures of crude oil and gaseous nitrogen. Gaseous nitrogen was used in lieu of methane gas as a safety precaution when testing oil/gas mixtures since it was felt that freezing performance would not be significantly different when using either methane or gaseous nitrogen in an oil/gas mixture. The various tests conducted, along with significant test results, are discussed below in Section E - Test Results.

Each test was conducted using the following sequence of events:

- (1) Data acquisition system on
- (2) Set conditions for display and recording of transducers
- (3) Compressed air supply on (125 psig)
- (4) Gaseous nitrogen supply on (500 psig)
- (5) Set valves for oil flow from supply tank through test sections into return tanks
- (6) Adjust air supply regulator to pressurize oil supply tank at 10-20 psig

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- (7) Open gate valve between supply tank and test section while monitoring visual readout of flow meter until desired oil flow rate is achieved
- (8) Set valves for  $\text{LN}_2$  flow into one or two test sections as desired
- (9) Record and display temperatures, pressures, and oil flow rate
- (10) Monitor oil flow rate and time until flow stops
- (11) After flow stops, set valves for pressure test of oil plug and apply  $\text{GN}_2$  pressure at test section inlet in increments of 50 to 100 psig up to a maximum pressure of 500 psig
- (12) Depressurize system and stop data recording system
- (13) Set valves and pumps for transfer of oil from return tanks to supply tank for next test

In addition to the above steps, the heating elements were turned on prior to the test in an effort to elevate the oil inlet temperature. As mentioned in section D.1, the test goal was  $75^\circ\text{C}$ . However, because of the electrical power supply problems at the test site, low ambient temperatures and heat loss from tanks and piping, the maximum oil temperature achieved was  $16^\circ\text{C}$ .

For testing of oil/gas mixtures, a supply of  $\text{GN}_2$  was introduced at the mixer section near the inlet of the test section (figure 7) and then the oil flow was started. Flow rates of gaseous nitrogen were not measured, nor was the flow rate of the  $\text{LN}_2$  since the incorporation of flow measuring devices for  $\text{GN}_2$  and  $\text{LN}_2$  was beyond the scope of this contract. Test results are discussed below.

### E. TEST RESULTS

Of the eleven tests conducted, four used one test section, five used two test sections, eight were conducted with oil only, and three with oil/gas mixtures. Testing included oil flow rates ranging from 3.8 gpm to 7.4 gpm. In all cases, the flowing fluid was effectively stopped by the formation of a frozen plug and the integrity of the frozen plug was demonstrated by pressure testing the plug up to 500 psig. Table 1 summarizes the test conducted and shown freezing time for each test.

TABLE 1. OIL SUPPLY TEMPERATURE

TEST NO.	FLOW (GPM)	FLUID	NO. OF TEST SECTIONS	OIL SUPPLY TEMP. (°C)	FREEZE TIME (MIN)	REMARKS
1	7.0	OIL	1	11.	48	FIRST TEST - LEARNING PROCESS
2	6.0	OIL	1	9.	16	PR. TEST TO 200 PSI AFTER FREEZE
3	NO TEST					TEST 3 FILE NOT USED
4	5.3	OIL	2	11.	21	PR. TEST OIL PLUG 200 PSI
5	NO TEST					TEST 5 FILE NOISEY
6	4.3	OIL	2	11.	27	APPARENT FREEZE AT 21 MINUTES THEN IMMEDIATE BREAK-THROUGH FOLLOWED BY HARD FREEZE AT 27 MINUTES.
7	*	OIL	*	*	*	INVESTIGATED LN <sub>2</sub> FLOW ADJUSTMENTS FOR OBTAINING LOWEST TEMPERATURE
8	*	OIL	*	*	*	INVESTIGATED DATA ACQUISITION SYSTEM.
9	7.4	OIL	2	*	31	PRESSURE TESTED OIL PLUG TO 190 PSIG.
10	5.5	OIL	2	*	25	PRESSURE TESTED OIL PLUG TO 400 PSIG.
11	3.8	OIL/GAS	1	6.	10	DEVELOPED PROCEDURES FOR OIL/GAS TESTS.
12	4.9	OIL/GAS	1	8.	43	AFTER 32 MINUTES, GN <sub>2</sub> WAS STOPPED.
DEMO 2	5.2	OIL/GAS	2	16.	24	DEMONSTRATION TEST.

\* NO DATA

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Tests 1 and 9 demonstrated simulation of the flow rates of 1000 barrels established for the representative well.

As noted in section D.1, a flow rate of 1,000 barrels per day of a mixture varying from pure crude oil to gas would be a representative blowing-out well for the test program. Test flow rates for test 1 and 9 of 7.0 and 7.4 gpm in the quarter-scale test model extrapolate to 28.0 and 29.6 gpm (960 and 1015 barrels/day) in the full scale device.

Tests 11, 12, and DEMO2 were attempts to investigate freezing of oil/gas mixtures. During these tests, it was concluded that flowing mixtures of oil and gas could be successfully frozen, but a means of measuring the amount of gas being introduced into the oil was necessary for further oil/gas testing. Table 1 shows oil supply temperatures ranging from 6 to 16°C. As noted earlier, a temperature of 75°C was established for the representative well and as shown in table 1 this temperature was not achieved. Attempts to elevate the oil supply temperature to 75°C were made using immersion heaters and insulation on the oil supply tank, but because of electrical power supply problems at the test site, low ambient temperatures, and heat losses in uninsulated components, the attempts were not successful. However, a comparison of TEST 4 and DEMO2 gave an indication that freezing time is not sensitive to oil supply temperatures. For DEMO2 the oil supply temperature was 16°C, an oil/gas mixture was being used, oil flow rate was 5.2 gpm, and freezing time was the same as for TEST 4 which had a similar flow rate and oil supply temperature of 11°C.

A composite plot of the testing conducted is shown in figure 11 which gives oil flow rate versus freeze time for each test. More data points would be desirable, but one conclusion that can be drawn from the figure is that flow rates of 4 to 7 gpm will be stopped in 20 to 30 minutes. There is also an indication that two test sections reduce freezing time, but more testing is necessary to quantify the effects of two test sections.

Specific results for oil flow rates, temperatures, and pressure versus time are shown in the computer-generated plots shown in appendix A.

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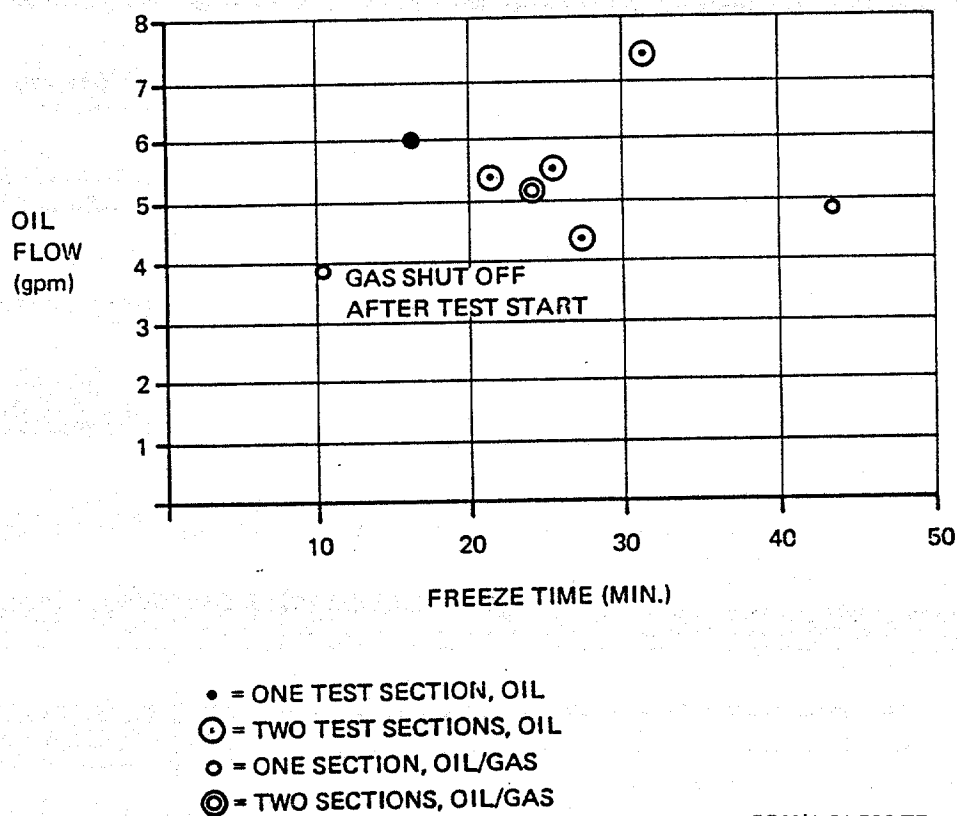


Figure 11. Flow Rate Versus Freeze Time

F. CONCLUSIONS AND RECOMENDATIONS

The results of this project have demonstrated that, in a one-quarter scale laboratory experiment, a cryogenic device can be used to effectively stop a flow of crude oil at oil flow rates of 4 to 7 gpm in 20 to 30 minutes. This data can be extrapolated to flow rates of 550 to 960 gpm in an actual well. Further, the extrapolation of test results using simulation studies indicate that for similar fluids the heat transfer coefficient in a full scale device would be one-fourth that in the model.

The freezing mechanism appears to occur by successive freezing of layers at the nonstationary boundary. Since the fluid velocity is zero at a boundary there may be some degree of independence from

- (1) gas/oil mixtures
- (2) fluid flow rates
- (3) fluid temperature

Additional work is necessary to evaluate these possibilities.

Three deviations from the proposed program plan should be noted (1) oil supply temperatures were lower than desired, (2) water mixtures were not used as proposed, and (3) strain measurements were not taken at the deflector blades as proposed.

Regarding the low oil supply temperatures, an oil temperature of 75° was established for the representative well at a typical DSD location, but oil test temperatures did not exceed 16°C. Attempts were made to raise the oil supply temperature to the test goal using immersion heaters and insulation on the oil supply tank; however, because of electrical power supply problems at the test site, low ambient temperatures and heat losses in insulated components, the desired oil temperature was not achieved. Modification of the test assembly and further testing is recommended to study effects on DSD performance of elevated oil temperatures.

Water mixtures were not tested since it was concluded prior to testing that the addition of water would expedite freezing; therefore,

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more effective use of test resources would be made by testing oil or oil/gas mixtures which represent worst-case fluids for the test program. Further study of oil/gas mixtures is recommended to quantify the device performance with oil/gas mixtures.

Measurement of strain in the deflector blades was planned, but not implemented. The special low-temperature strain gauges were ordered, strain measurement details worked out (including temperature compensation techniques), and the data acquisition system developed to include strain measurement and recording. However, because of an internal shipping problem, the strain gauges were not available at the required assembly time and the test section was assembled without them. A stress analysis was conducted in lieu of stress measurements and demonstrated that the deflector blade concept would restrain a frozen plug during oil pressures up to 39000 psi in a full scale device, which is well beyond the maximum downhole pressure of 20000 psi established for the representation well.

The test program conducted has verified the "proof of principle" for developing a cryogenic valve to control blowing-out wells. Additional effort as follows is recommended for development of the DSD:

- (1) Quantify the physical phenomena
- (2) Use the existing quarter-scale facility to develop and verify an analytical model of the cryogenic valve, then pursue the technology to full scale
- (3) Use the analytical model to design a full scale prototype for operational testing
- (4) Construct prototype and test at LSU
- (5) Use LSU test results to refine model
- (6) Use model to design hardware for application to actual oil well
- (7) Construct hardware and install in an actual oil well to collect final development test data
- (8) Identify and address operational problems (they are only guessed at now)

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APPENDIX A  
TIME-HISTORY PLOTS OF TEST RESULTS

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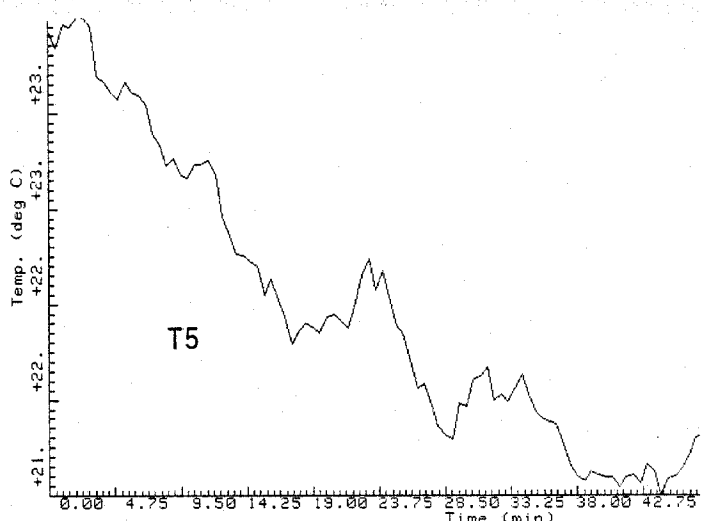
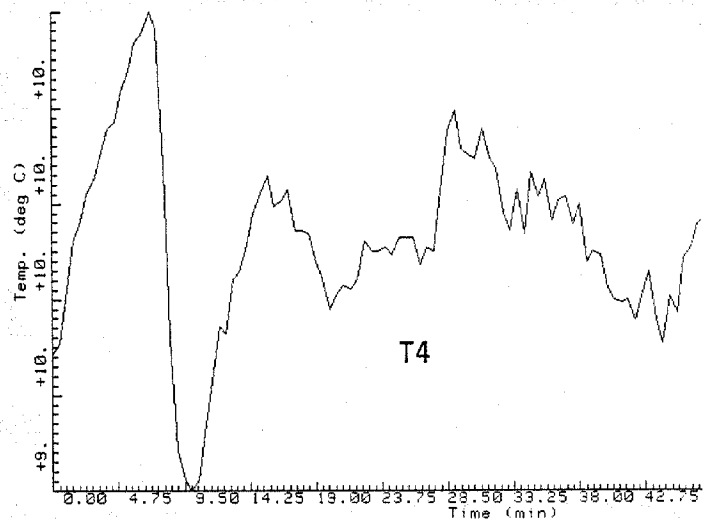
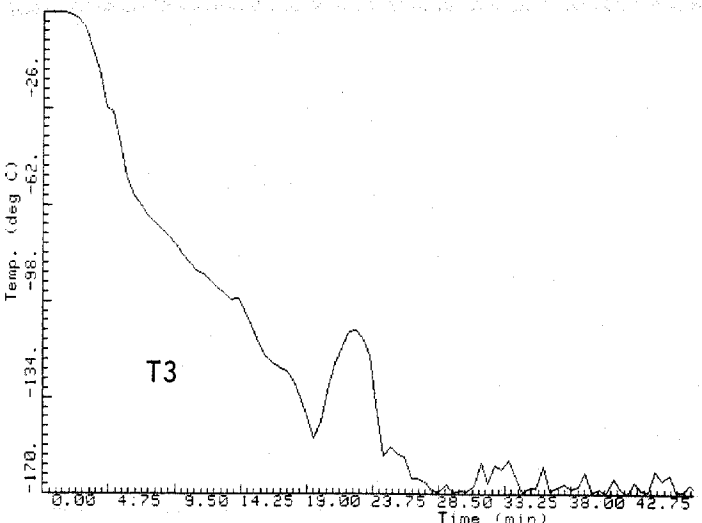
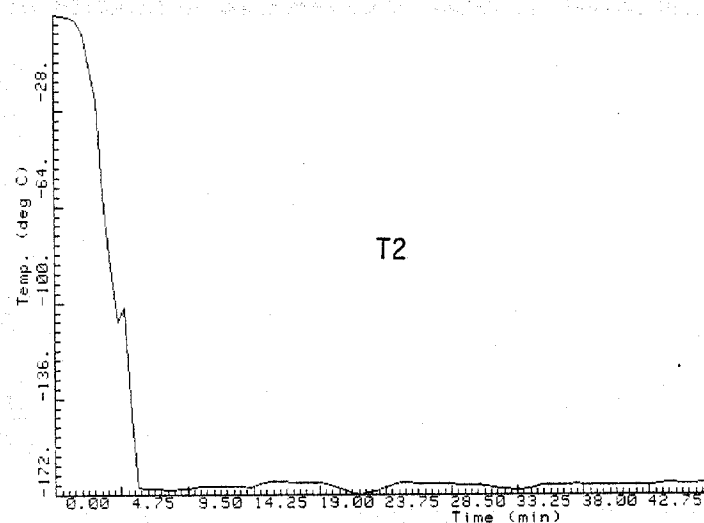
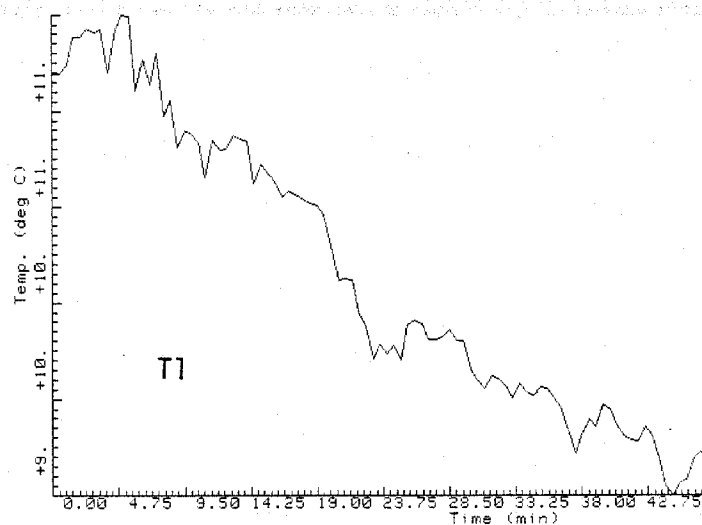
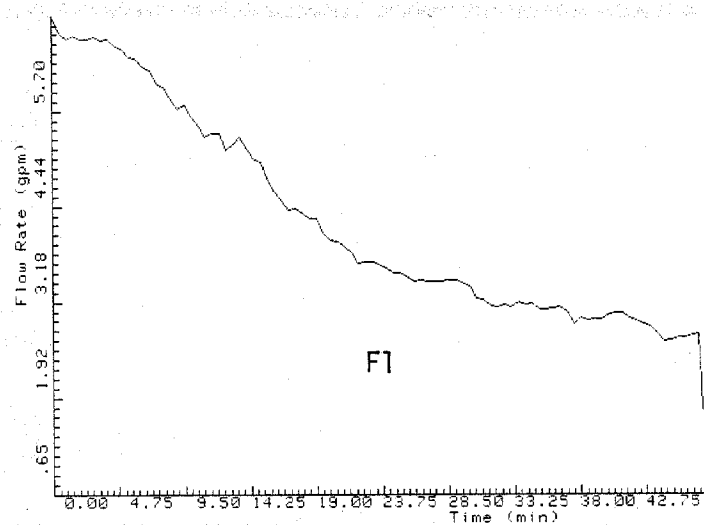


Figure A-1. TEST 1 Results

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